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EXPLANATION OF RANDOM EXPERIMENT SCHEDULING AND ITS APPLICATION TO SPACE STATION ANALYSIS

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16. Abstract

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The REPRI program uses the Monte-Carlo technique to generate a set of feasible experiment schedules for a Space Station. The schedules are statistically analyzed to determine the impact of the station experiment program resource requirements on the station concept. Also, the sensitivity of the station concept to one or more resources is assessed.

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DEFINITION OF TERMS

Blue Book - A compendium of Functional Program Elements derived for use in the design of a multidisciplinary orbital space facility.

Candidate Experiment Program (CEP) - A schedule of functional Program Elements selected from the Blue Book which can realistically be completed by the Space Station concept being considered.

Functional Program Element (FPE) - A group of experiments which are mutually supportive of a specific research area and which will impose similar demands on an orbital system.

EXPLANATION OF RANDOM EXPERIMENT SCHEDULING AND ITS APPLICATION TO SPACE STATION ANALYSIS

SUMMARY

This report analyzes the capability of the McDonnell-Douglas Phase B Space Station concept to complete the Blue Book Experiment program and describes the Random Experiment program with Resource Impact (REPRI) which was used to generate the data. The results indicate that station manpower and electrical power are the two resources which will constrain the amount of the Blue Book program that the station can complete. The station experiment program and its resource requirements are sensitive to levels of manpower and electrical power below 13.5 men and 11 kilowatts. Continuous artificial gravity experiments have much less impact on the experiment program than experiments using separate artificial gravity periods. Station storage volume presently allocated for the FPE's and their supplies (1600 ft^3) is more than adequate.

The REPRI program uses the Monte-Carlo technique to generate a set of feasible experiment schedules for a Space Station. The schedules are statistically analyzed to determine the impact of the station experiment program resource requirements on the station concept. Also, the sensitivity of the station concept to one or more resources is assessed.

I. INTRODUCTION

NASA is presently designing a Space Station which will serve as a general purpose laboratory for scientific research in earth orbit. Research will be conducted in earth surveys, astronomy, astrophysics, biomedicine, biology, and space physics. A wide variety of resources and equipment will be required to support such a versatile facility.

The design of a complex Space Station requires a mission planning tool to determine resource requirements, compare different station concepts, and perform sensitivity studies. During the Phase B Space Station study, McDonnell-Douglas developed a deterministic scheduling program which puts man in the loop as the decision maker. Using this model, twenty-six different candidate experiment programs were generated from the Blue Book before arriving at a baseline experiment program. Since a priority listing of the Blue Book experiments was assumed, there

is no statistical assurance that the resource requirements of these cases are representative of the true mean candidate program.

In order to generate meaningful statistical data on all possible candidate experiment programs that can be selected from the Blue Book, a model was developed which performs random scheduling and statistical evaluation of the large sample of schedules generated. This model, described in Section II, has been used to support the evaluation of the McDonnell-Douglas Phase B Space Station Concept.

Section III describes the impact of the Blue Book experiment program resource requirements on the station concept. The sensitivity of the experiment program and its resource requirements to station manpower and electrical power available for direct support of the experiment program is analyzed in Section IV, as well as the sensitivity of the station experiment program to the artificial gravity period. Section V describes the present logistics capability of the REPRI program and presents the logistics requirements of a typical candidate experiment program. Section V also describes the new REPRI logistics routine which is presently being developed.

II. RANDOM EXPERIMENT PROGRAM WITH RESOURCE IMPACTS (REPRI)

In order to design a complex Space Station, a mission planning tool is required to determine resource requirements, compare different station concepts, and perform sensitivity studies. A mathematical model has been developed which meets these requirements. The model uses the Monte Carlo technique to generate candidate experiment programs from a list of proposed experiments. A candidate experiment program (CEP) is generated by randomly scheduling as many of the proposed experiments as possible without exceeding any of the available station resources. After a large sample of CEP's has been developed, statistical methods can be applied to determine ranges on resource requirements and other selected parameters such as the percent completion of the proposed experiment list. In addition, an indication of the compatibility of a given experiment with the station concept can be obtained from the number of times the experiment was scheduled in the sample.

This model has been used to support Marshall Space Flight Center in its evaluation of the MDAC Phase B Space Station effort [1]. The candidate experiments used by MDAC in their Phase B effort were taken from the NASA "Blue Book" (Candidate Experiment Program for Manned Space Station). The Blue Book was designed to provide criteria, guidelines, and an organized approach for developing a flexible, multidisciplinary orbital space facility design. It also defines a manned

space flight experiment program that can be accomplished in the early years of an earth orbital Space Station mission and will fully utilize the Space Station facility. To define such a comprehensive experiment program, a heterogeneous collection of individual experiments is not practical; therefore, the term "Functional Program Element" (FPE) was adopted to describe a gross grouping of experiments characterized by two dominant features: (1) individual experiments that are mutually supportive of a particular area of research or investigation, and (2) experiments that impose similar and related demands on the Space Station support system. MDAC, and consequently this report, uses "experiment" and "FPE" interchangeably.

Figure 1 shows a random candidate experiment program generated in this analysis. A candidate program is represented by an n x m array, where each row is associated with a functional program element (FPE) and each column is associated with a unit time interval. The 10-year space station mission was divided into twenty 6-month intervals in this example. A one in row I and column J indicates that the FPE listed to the left of row I is scheduled in interval J; a zero indicates that the FPE listed to the left of row I was not scheduled in interval J.

In Figure 1, the column entitled "Performance Required" specifies the number of intervals in which each FPE is required to be operated. The column entitled "Performances Scheduled" gives the number of intervals in which each FPE was scheduled. All required performances of each FPE are not always scheduled, because of either a lack of resources or a conflict with another FPE. The last column on the right side of figure 1 specifies the FPE mode of accommodation. The abbreviations FF, AM, and I stand for free-flying module, attached module, and integral accommodations, respectively.

A candidate experiment program is generated by, first, randomly ordering all the FPE's in the proposed experiment program, and then considering the FPE's for scheduling one at a time from the random ordering. Performance requirements of an FPE are met by scheduling in one interval at a time. Two conditions must be satisfied before an FPE will be scheduled in an interval: (1) Sufficient station resources must be available to operate the FPE, and (2) no other FPE which conflicts with the FPE being scheduled must have been previously scheduled in the interval. If an FPE is scheduled in an interval, the available station resources in the interval are reduced by the resource requirements of the FPE.

The available station resources presently being considered are manpower, electrical power, station storage volume, and data handling requirements. The amount of each resource available must be specified for each interval so that the resources can be changed during the mission. An unconstrained resource is defined by specifying that a very large amount is available in each interval.

The first interval in which an FPE is scheduled can be either fixed or randomly selected to occur on or after a first possible start interval. If the first scheduling interval is not fixed, the scheduling intervals are randomly ordered. A first scheduling interval is selected by checking the intervals in the random ordering until one is found which occurs on or after the first possible start interval. If the resource requirements of the FPE cannot be satisfied in the selected interval, this process is continued until either an acceptable start interval is found or all the randomly ordered intervals have been checked.

The model attempts to place all performances of an FPE as close together as possible in time. After an acceptable start interval is found for an FPE, performances of the FPE are scheduled in subsequent intervals until one of the following events occur:

(a) An interval with an insufficient resource (other than station storage volume) is encountered.

(b) An interval with insufficient station storage volume is encountered.

(c) All performances are scheduled.

(d) The end of the mission is encountered.

(e) A scheduling conflict is encountered.

If (a) occurs, the interval is skipped and scheduling is attempted in subsequent intervals. If either (b), (d), or (e) occurs before (c), performances are scheduled backward in time beginning with the first interval preceding the start interval. Backward scheduling continues until the first possible start interval is encountered or (a), (b), (c), or (e) occurs. No further attempt is made to schedule performances of the FPE if any of these events except (a) occurs. If (a) occurs, the interval is skipped and backward scheduling continues. Note that the scheduling technique does random scheduling, yet it considers FPE conflicts, fixed start dates, first possible start dates, and station resource constraints. Also, as much as possible of the required performance of each FPE is scheduled.

After a candidate program has been generated, the resources required for direct support of the experiment program are summarized by interval (see figure 1). The resources are summarized as follows:

A WATTS	The average watts of electrical power required.
KW-HRS	The kilowatt-hours of electrical power required.
BIT RT	The number of telemetry bits that must be telemetered each day during the interval.
MAN HRS	The number of manhours required.
SKILL i	The number of manhours required of skill i. The sum of the manhours required of each skill in a given interval equals the number of manhours specified under MAN HRS for the interval.
S WT UP	The supply weight that must be available on orbit to operate the FPE's that are active during an interval. Supplies include only the operational consumables, maintenance consumables, and spares required for direct support of experiments.
S VOL UP	The supply volume corresponding to the supply weight given by variable S WT UP.
RET WT	The logistic weight to be returned from orbit. The weight of each FPE (including its module if applicable) is included in the last interval in which the FPE operates. Included in each interval in which an FPE is active are the weights of data (such as film, etc.) and of used experimental equipment to be returned from orbit. The weight of crew and station supplies to be returned is not included.
RET VOL	The logistic volume corresponding to RET WT that is to be returned from orbit.
E WT UP	The weight of each FPE (including its module if applicable) and its initial supplies is included in the first interval in which the FPE is scheduled.
E VOL UP	The logistic volume corresponding to E WT UP to be carried to orbit.
SS VOL	Space Station volume required to store the FPE's and their supplies. The volume of the FPE's accommodated by free flying and attached modules is not included; however, their supply volume requirements are included.

PC COMPL — The cumulative percent of the proposed experiment program completed. For the ith interval, the cumulative percent completed is computed by dividing the sum of all the 1's in the first i columns of the scheduling array by the sum of all entries in the "performances required" column and multiplying the result by 100. Thus, the performance of one FPE in one interval was chosen as the basic unit for computing percent completion.

COST PER YEAR — This section specifies the FPE development cost per year, as well as the cumulative FPE development cost. These data include the cost of developing the FPE's and delivering them to the launch facility and the cost of developing and building the free-flying and attached modules. FPE operating cost is not included.

The model has the capability of generating N candidate experiment programs (CEP's) where N is specified by the user. As the N programs are generated, the average and maximum values are computed by interval for the parameters summarized at the end of each schedule. Figure 2 shows both the frequency distribution of scheduling that was generated and the averages for a sample of 200 schedules. In this sample, FPE 10 was scheduled 173 times in interval 4, and an average of 8231 manhours was required in interval 1. The frequency distribution of scheduling shows how compatible each FPE is with the Space Station concept being analyzed. A time history of the output parameters (manhours, average watts, etc.) can be obtained by plotting the averages for the individual intervals. Figure 3 shows the maximum values of the same parameters for the sample. The maximums are determined by interval and not by CEP. For example, the maximum number of manhours for two different intervals will most likely be from two distinct CEP's.

A great deal can be learned about the entire population of all possible CEP's for the station concept being considered by applying statistical theory to the sample. Maximum ranges for the parameters summarized can be established for specified levels of probability and confidence, which are dependent on the sample size. For example, a sample of 100 CEP's gives 97 percent confidence that the resource requirements of 95 percent of all possible CEP's for the station concept considered will be less than the maximum resources of the sample (see appendix A). Ranges for the true mean of the parameters summarized can also be established for specified levels of confidence (see appendix B).

III. SPACE STATION RESOURCE CONSTRAINTS

The REPRI program described in Section II has been used to determine the ability of the Space Station to complete the Blue Book experiment program. The analysis was performed on a Functional Program Element (FPE) and one-month level of detail. A 10-year mission initiated with five periods of artificial gravity experimentation was assumed, each artificial gravity period to last one month and each period to be followed by two months of zero gravity. The first gravity period was assumed to begin the second month of the mission. It was further assumed that five FPE's will be accommodated in free-flying modules and six FPE's will be accommodated in attached modules. The amount of the Blue Book program that could be completed by a Space Station with unlimited resources was determined to be an average of 89 percent and a maximum of 90 percent. However, approximately 13 astronauts and 11 kilowatts of electrical power would be required to support only the experiment program. Thus, manpower and electrical power appear to be the two constraining factors in determining the percentage of the Blue Book experiment program that could be accomplished.

Next, the station capability was analyzed by constraining manpower and electrical power. The constraining values used were 10.5 astronauts for manpower [1] and 8 kilowatts of electrical power, since these are the values that the MDAC Phase B analysis shows will be available. Table 1 summarizes the results of the two cases. The manpower and electrical power constraints reduce the average amount of the Blue Book program that can be completed by 12 percent and the maximum amount by 8 percent. Also, note that Space Station storage volume is not a constraint even with unlimited resources.

The data presented in Table 1 were obtained from the summary of 200 CEP's. Two hundred CEP's gives a 99 percent confidence that the resource requirements of 95 percent of all possible candidate programs for the case in question will be less than the maximum resources of the sample. (The statistical theory on which these percentages are based is presented in appendix A).

Figure 4 shows the time histories of the mean and maximum manpower requirements for the two cases summarized in Table 1 (the unconstrained and the man hours and electrical power constrained cases). The manpower requirement is lower during the first 15 months, because only half, or less, of the FPE's can be operated during the artificial gravity period. McDonnell-Douglas' latest analysis [1] indicates that 10 to 11 of the 12 astronauts on board the station will be available to support the experiment program. The 13-man requirement of the unconstrained case indicates that manpower would be a station constraint. Most of this manpower requirement (6.4 men) comes from FPE 5.13, the biomedical experiments, which require 10 years of operation.

TABLE 1

MEAN (MAX) EXPERIMENT PROGRAM REQUIREMENTS FROM RANDOM SCHEDULING

CASE DESCRIPTION*	% OF TOTAL EXPERIMENT PROGRAM COMPLETED	NUMBER OF ASTRO-NAUTS	AVERAGE ELECT. POWER (watts)	SS STORAGE VOLUME (ft^3)	TOTAL FPE DEVELOPMENT COST (10^9 dollars)	DATA HANDLING (10^9 bits / day)
PRESENT SS CONSTRAINTS	– (–)	10.5 (–)	8,000 (–)	1,600 (–)	– (–)	– (–)
NO CONSTRAINTS	89 (90)	11.7 (12.7)	10,700 (11,200)	970 (1,400)	1.79 (1.83)	793 (797)
MAN HOURS & ELECTRICAL POWER CONSTRAINED	[65] 77 (81)	9.1 (10.5)	7,550 (8,000)	880 (1,340)	1.76 (1.83)	575 796

* TWO HUNDRED RANDOM SCHEDULES WERE GENERATED FOR EACH CASE DESCRIBED. ALSO, ALL CASES CONSIDER DOCKING PORT CONFLICTS AND ARTIFICIAL GRAVITY CONFLICTS.

[] THIS PERCENT IS FOR THE McDONNELL DOUGLAS CASE 26.

Figure 5 shows a breakdown of the mean crew skills, where both manpower and electrical power are constrained. (Table 2 defines the skill codes.) Crew skill mix was not considered as a constraint during the derivation of the data.

Table 2. Skill Mix Code

Skill Number	Skill Type	Training Required
1	Astrophysicist	Physics Metallurgy
2	Biologist	General Biology Equipment Maintenance
3	Physiologist	Physiology Equipment Maintenance
4	Physician	Medicine Behavioral Science
5	Physician	Medicine Equipment Maintenance Behavioral Science
6	Biomedical Engineer	Instrumentation Operation/Maintenance (Biomedical)
7	Electrical Engineer	Mechanics Equipment Maintenance
8	Electro/Mechanical Engineer	Equipment Maintenance Earth Resources Data Interpretation
9	Subject	Special Equipment Use

Time histories of the mean and maximum electrical power requirements for the two cases are shown in figure 6. Electrical power requirements are lower during the first 15 months because of the artificial gravity experiment. The allocation of 8 kilowatts of power to the FPE's comes from reference 2. The 10.7 kilowatts of power required by the mean

unconstrained CEP shows electrical power to be a major Space Station constraint. However, a large part of the 10.7 kilowatt requirements comes from the attached modules, each of which requires a constant one-kilowatt power supply just to operate and maintain its subsystems.

The cumulative percentage of the Blue Book program completed is shown in figure 7. The total Blue Book program was not completed in the unconstrained case because of two FPE conflicts and because nine of the FPE's require ten years of operation and cannot be operated during the first 15 months when the artificial gravity experiment is being performed. The manpower and electrical power constrained case indicates that a maximum of 82 percent and an average of 77 percent of the Blue Book program can be completed. Note that completion of 70 percent of the Blue Book program requires approximately one year longer in the constrained resource case than in the unconstrained case.

The Space Station volume required for storage of the FPE's and their supplies is shown in Figure 8. Although the volume of the FPE's accommodated by free-flying and attached modules is not included, their supply volume requirements are included. The volume available for storing supplies in the crew/cargo module was not considered in this analysis. This figure shows that Space Station storage volume is not a problem at this time.

The data in figure 9, which presents the cumulative FPE development cost, include the cost of developing the FPE's and delivering them to the launch facility, but do not include FPE operating cost. Also included is the cost of developing and building the attached and free-flying modules. (The cost data are based on 1970 prices and do not include an inflation factor.) Figure 10 shows the electronic data handling requirements on board the Space Station.

Logistic requirements of the Space Station will be discussed in Section IV.

IV. SENSITIVITY OF SPACE STATION EXPERIMENT PROGRAM TO MANPOWER, ELECTRICAL POWER, AND DURATION OF ARTIFICIAL GRAVITY EXPERIMENT

The analysis presented in Section III has been extended to include the sensitivity of the experiment program and its resource requirements to station manpower and electrical power available for direct support of the experiment program. The sensitivity of the station experiment program to the length of the artificial gravity period has also been analyzed. The analysis was performed on a Functional Program Element (FPE) and one-month level of detail.

The amount of the Blue Book program that can be completed is sensitive to levels of manpower and electrical power below 13.5 men and 11 kilowats. Also, station resources of 13.5 men and 11 kilowatts of power would be optimum for performing the maximum percentage of the Blue Book program. Unit increases in either the present station manpower (10.5 men) or electrical power (8 kilowatts) do not significantly increase the percentage completed. Therefore, only large increases to the present station manpower and electrical power levels will make the station more efficient. However, a unit decrease in either resource significantly decreases the percentage completed. Other station resources, such as FPE development cost, station storage volume, and station data handling requirements, are sensitive to levels of manpower and electrical power below 13.5 men and 11 kilowatts.

The sensitivity data were developed by generating 200 random candidate experiment programs (CEP's) for different combinations of manpower and electrical power. Manpower was varied between 6 and 15 men; electrical power was varied between 6 and 14 kilowatts. None of the station parameters were found to change for manpower above 13.5 men and electrical power above 11 kilowatts.

Two hundred random candidate experiment programs constrained to fixed levels of manpower and electrical power gives 99 percent confidence that the resource requirements of 95 percent of all possible candidate programs for the fixed constraints will be less than the maximum resources of the sample.

Table 3 shows the maximum amount of manpower required by the experiment program as a function of the electrical power available for direct support of the experiment program. It also shows that 13.5 men is the maximum amount of manpower the experiment program will require. Each data point was obtained from the summary of 200 CEP's. A point was generated by constraining electrical power to a fixed level and allowing manpower to be unconstrained.

Table 3. Maximum Manpower Required by Station Experiment Program versus Electrical Power Available

Electrical Power Available	Maximum Manpower Required
6 kilowatts	11.9 men
7	12.2
8	12.7
9	13.1
10	13.4
11	13.5
12	13.5
13	13.5
14	13.5

Figure 11 presents the mean percentage of the Blue Book program completed as a function of electrical power and manpower available. The two dashed lines about each solid line defines the 95 percent confidence interval limits; i.e., there is 95 percent confidence that the true mean lies between the two dashed lines. This figure indicates that the mean percentage of completion is insensitive to manpower above 13.5 men and electrical power above 11 kilowatts. Also, 13.5 men and 11 kilowatts of power would be optimum for completing the largest amount of the Blue Book program. The present station manpower (10.5 men) and electrical power (8 kilowatts) appear to be an optimum local point. That is, a unit increase in manpower or electrical power increases the amount completed by only 1 percent, but a unit decrease in manpower or electrical power decreases the amount completed by approximately 3 percent.

Figure 12 shows the sensitivity of both the mean and maximum percentage of completion to manpower and electrical power. The mean sensitivity data (figure 11) are presented for contrast with the maximum sensitivity data. Note that the difference between the mean and maximum percentage of completion decreases as the number of men available increases. When only a few men are available to perform experiments, the percentage of completion is directly dependent on the number of FPE's scheduled which require a large amount of manpower. For example, FPE 5.13 (the biomedical experiments) requires 6.4 men to operate and represents only 11 percent of the Blue Book program. In contrast, there are 9 FPE's which require a total of only 2.1 men; these represent approximately 51 percent of the Blue Book program. As the number of men available is increased, the percentage of completion becomes less dependent on which FPE's are scheduled and the difference between the mean and maximum decreases.

Figure 13 shows the sensitivity of FPE development cost to manpower and electrical power. These data include the cost of developing the FPE's and delivering them to the launch facility, but do not include FPE operating costs. Also included is the cost of developing and building attached and free-flying modules. This figure shows that FPE development cost is sensitive to manpower and electrical power below 13.5 men and 11 kilowatts.

Figure 14 shows the sensitivity of station data handling requirements (bit rate) to electrical power and manpower. Only the electronic data to be handled on board the Space Station are included. Hard copy data are not included.

The McDonnell-Douglas Phase B Space Station study indicates that 6,400 cubic feet (1.25 decks) will be available for experiment use inside the station. However, for each cubic foot of stored experiment, 4 cubic feet of station volume will be required for installation and

operation. Thus, 1,600 cubic feet will be available on the station for use in storing experiments.

The sensitivity of experiment storage volume to station electrical power and manpower is shown in figure 15. The data include the volume required to store the FPE's and their supplies. The volume of the FPE's accommodated in free-flying and attached modules is not included; however, their supply volume requirements are included. Figure 15 indicates that the mean station storage requirements will not exceed the 1,600 cubic feet available.

The impact of three different artificial gravity experiments on the station experiment program has been assessed. These experiments are described as follows:

(1) Five one-month periods of artificial gravity was assumed with the first period beginning the second month of the mission. Each period is followed by two months of zero gravity.

(2) A one-month artificial gravity experiment beginning the second month of the mission was assumed next.

(3) A continuous four-month artificial gravity experiment beginning the second month of the mission was assumed last.

For all three gravity experiments, no free-flying and attached modules can be carried to orbit before the end of the gravity experiment; however, integral FPE's can be operated before and after the gravity period.

All three artificial gravity experiments assumed that FPE's 5.13A, 5.24E, 5.24F, 5.24G, 5.6, 5.14, 5.17, 5.18, and 5.22 can be operated during artificial gravity.

Two hundred CEP's were generated for each artificial gravity experiment assuming that the station manpower and electrical power supporting the experiment program are constrained to 10.5 men and 8 kilowatts, respectively. The mean and maximum cumulative percentage of the Blue Book program completed for each artificial gravity experiment is shown in figures 16 and 17. Note that an average (maximum) of 2.3% (3.0%) more of the Blue Book is completed with four continuous months of gravity than with five separate one-month periods. However, an average (maximum) of only 1.2% (1.6%) more of the Blue Book is completed with the one-month of gravity than with the four continuous months of gravity. The five separate gravity periods have the greatest impact on the experiment program because the free-flying and attached modules cannot be carried to orbit before the 15th month.

Figures 16 and 17 also show that the impact of the different gravity experiments is to change the time required to complete a given amount of the mission. Completing 75 percent of the Blue Book requires an average of 111 months for one month of gravity, 114 months for four continuous months of gravity, and 117 months for five separate gravity periods. Thus, increasing the continuous gravity period from one to four months delays attainment of the experiment program 75 percent completion point by 3 months, and changing the gravity experiment from four continuous months to five separate one-month periods delays this milestone by an additional 3 months.

V. LOGISTICS

The REPRI program described in Section II computes only very gross logistic requirements for each random candidate experiment program (CEP) it generates. The gross logistic parameters summarized for each CEP, described in Section II, are, for each interval, supply weight and volume to be carried to orbit, experiment weight and volume carried to orbit, and total weight and volume returned from orbit. The program does not presently have the capability of considering logistic requirements as constraining factors in the generation of a CEP.

The logistic requirements of a typical CEP with station manpower and electrical power constrained to 10.5 men and 8 kilowatts are shown in figures 18-21. The assumptions given at the beginning of Section III were applied when this CEP was generated. Figures 18 and 19 show the logistic weight and volume that must be carried to orbit each quarter of a year. Included in the first quarter in which an FPE is scheduled are the weight and volume of the FPE and its initial supplies. The quarterly resupply weight and volume requirement of an FPE are included in each quarter in which the FPE is active. Figures 20 and 21 present the logistic return weight and volume requirements for each quarter of a year. The weight and volume required for return of each FPE are included in the last quarter in which the FPE operates. This is the reason the return weight and volume is so large in the last quarter year of the mission. Also included in each quarter in which an FPE is active is the weight and volume of hard copy data and used experimental equipment parts.

Note that the weight and volume that must be carried to orbit in the quarter following the end of the artificial gravity experiment is 155,000 pounds (figure 18) and 54,400 cubic feet (figure 19). These requirements contain the weight and volume of one free-flying module and five attached modules. Four free-flying modules and five attached modules require 10 years of operation. Therefore, they must be carried

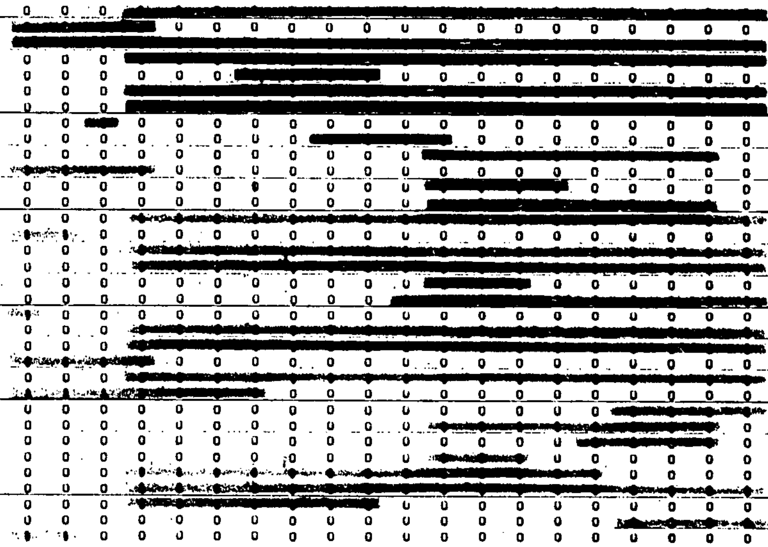
to orbit at the first opportunity in order to complete as much of their performance as possible. However, this requirement is unrealistic for the Advanced Logistics System in a three-month period.

In order to make the logistic requirements of a CEP generated by the REPRI program realistic, a logistic routine is being developed which will constrain the scheduling of experiments. This new routine will package payloads and launch vehicles as they are required. The number of vehicles available, their payload capability, and the turn-around (refurbish) time will be used to compute logistic constraints. A complete logistic profile will then be available for each CEP generated. After a large sample of CEP's are generated, the logistic requirements of the sample can be summarized and statistically analyzed. The results will show the number of launches required and the descriptions of their payload requirements for each unit interval of time. This routine is expected to be operational by November 1970.

CANDIDATE EXPERIMENT PROGRAM

SCHEDULE 6

INTERVAL 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20



SCHEDULE	PERFORMANCES REW	PERFORMANCES SCHD	MODE OF ACCOMMODATION
FPE 260	20	17	1
FPE 170	4	4	1
FPE 131	20	20	1
FPE 10	20	17	FF
FPE 270	4	4	1
FPE 250	20	17	1
FPE 91	20	17	AM
FPE 60	1	1	1
FPE 160	4	4	1
FPE 73	8	8	1
FPE 180	4	4	1
FPE 120	4	4	FF
FPE 75	8	8	1
FPE 110	20	17	AM
FPE 246	2	2	1
FPE 30	20	17	FF
FPE 150	20	17	1
FPE 72	3	3	1
FPE 200	10	10	AM
FPE 220	1	1	1
FPE 100	20	17	1
FPE 92	20	17	AM
FPE 247	4	4	1
FPE 20	20	17	FF
FPE 140	7	7	1
FPE 40	4	4	AM
FPE 74	8	8	1
FPE 50	4	4	FF
FPE 71	3	3	1
FPE 210	20	13	AM
FPE 132	20	17	AM
FPE 80	20	7	FF
FPE 244	4	4	1
FPE 245	2	2	1

SUMMARY OF RESOURCES

INTERVAL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A WATTS	1203	635	665	10853	10676	10676	10721	10554	10703	10703	10622	11041	10872	10872	10871	10904	11029	11029	11029	10598
KW-HRS	7092	696	774	40074	39774	39774	39906	39756	41298	41298	45870	47514	45972	45972	45942	45942	45972	45972	45972	44358
BIT RT	70	67	84	79555	79554	79554	79558	79558	79565	79565	78698	78762	78755	78755	78750	78743	78608	78608	78608	78556
MAN HRS	8214	6888	6756	19584	18420	18420	18810	17586	18054	18054	17760	19494	19026	19026	17874	18222	18648	18648	18648	17718
SKILL 1	510	30	0	1278	1278	1278	1626	1626	1944	1944	1362	1644	1326	1326	1266	1542	1560	1560	1560	1062
SKILL 2	0	0	0	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092
SKILL 3	0	0	0	948	948	948	948	948	948	948	948	948	948	948	948	948	948	948	948	948
SKILL 4	1338	1338	1338	1788	1746	1746	1746	1746	1746	1746	1746	1746	1746	1746	1746	1746	1746	1746	1746	1746
SKILL 5	1500	1500	1500	2172	2112	2112	2112	1806	1806	1806	1806	1806	1806	1806	1806	1806	1806	1806	1806	1806
SKILL 6	0	0	0	1602	1602	1602	1602	1602	1602	1602	1602	1602	1602	1602	1602	1602	1644	1644	1644	1644
SKILL 7	2040	1194	1164	2760	1962	1962	1962	1596	1656	1656	1932	2352	2292	2292	2160	2202	2346	2346	2346	2016
SKILL 8	450	450	378	2670	2406	2406	2448	2436	2526	2526	2538	3570	3480	3480	2520	2550	2772	2772	2772	2670
SKILL 9	2376	2376	2376	5274	5274	5274	5274	4734	4734	4734	4734	4734	4734	4734	4734	4734	4734	4734	4734	4734
S WT UP	1134	1116	1020	10866	10056	10056	10884	10746	11136	11136	9234	15558	15168	15168	14946	9900	9822	9822	9822	8766
S VOL UP	24	24	24	822	810	810	840	834	858	858	610	912	888	888	876	798	798	798	798	786
RET WT	8752	5154	1207	22191	18498	18498	19277	18552	18840	60551	18588	20227	18373	18899	25631	38070	18643	18643	51791	233283
RET VOL	150	221	32	604	482	482	537	500	512	8690	488	591	476	500	7364	7370	488	488	11117	71083
E WT UP	16192	0	1572	31370	0	0	1287	0	1566	0	21916	9122	0	0	0	31828	20098	0	0	0
E VOL UP	771	0	8	71203	0	0	53	0	103	0	6888	6993	0	0	0	10598	7204	0	0	0
SS VOL	795	675	492	1568	1446	1446	1529	1492	1619	1619	1618	1675	1598	1598	1512	1434	1760	1760	1760	1707
PC COMPL	2	4	6	11	15	19	23	27	31	36	40	46	51	56	61	66	71	76	82	86

COST PER YEAR (MILLION DOLLARS)

1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
.00	17.70	80.60	177.32	294.58	349.95	323.67	247.84	115.54	26.13
.00	17.70	98.30	275.62	570.21	920.16	1243.83	1491.67	1607.21	1633.38
1980	1981	1982	1983	1984	1985	1986	1987	TOTAL	
40.15	49.58	46.66	39.70	21.39	.00	.00	.00	1830.89	
1673.50	1723.08	1769.74	1809.44	1830.89	1830.89	1830.89	1830.89		

FIGURE 1

FREQUENCY DISTRIBUTION OF SCHEDULING FOR 200 SCHEDULES

INTERVAL		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	PERFORMANCES REQ	PERFORMANCES SCHD
FPE	10	0	0	0	173	180	186	182	188	186	185	188	189	187	189	189	191	188	190	191	192	20	16
FPE	20	0	0	0	184	189	188	187	190	186	182	183	190	186	186	188	189	190	187	188	189	20	16
FPE	30	0	0	0	176	166	167	170	170	171	169	167	170	172	174	174	172	170	173	172	170	20	15
FPE	40	0	0	0	2	7	10	14	20	20	20	20	21	21	28	31	31	49	41	34	26	4	2
FPE	50	0	0	0	6	20	37	50	58	54	50	46	43	40	44	46	43	76	65	55	51	4	4
FPE	60	0	0	200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
FPE	71	0	0	0	11	17	27	21	30	33	43	37	38	33	34	31	27	30	61	55	43	3	3
FPE	72	0	0	0	12	26	38	36	33	32	38	39	36	33	30	34	34	39	60	46	34	3	3
FPE	73	0	0	0	10	27	36	47	65	81	92	98	96	162	156	140	134	120	109	106	99	8	8
FPE	74	0	0	0	17	26	37	53	66	78	87	93	97	160	152	140	131	121	108	101	91	8	8
FPE	75	0	0	0	15	26	31	42	59	69	81	98	99	162	156	146	135	128	111	93	83	8	8
FPE	80	0	0	0	158	167	164	160	156	149	144	91	91	91	95	97	101	109	108	111	113	20	11
FPE	91	0	0	0	136	138	138	134	136	136	135	135	137	133	132	133	133	131	131	133	133	20	11
FPE	92	0	0	0	151	150	147	151	147	147	149	149	150	148	144	144	144	143	148	145	149	20	13
FPE	100	0	0	0	163	168	168	168	172	171	169	168	170	167	169	167	166	169	170	167	169	20	14
FPE	110	0	0	0	127	131	128	127	130	131	131	131	130	132	133	135	133	132	132	102	135	20	11
FPE	120	0	0	0	16	27	43	55	49	54	52	48	51	40	38	36	40	78	67	59	47	4	4
FPE	131	200	200	200	157	169	166	165	177	173	173	172	168	165	169	168	170	170	172	174	174	20	17
FPE	132	0	0	0	121	130	128	128	137	135	132	132	130	132	133	137	134	132	133	134	136	20	11
FPE	140	200	200	200	170	172	173	176	14	9	7	4	3	1	2	1	1	3	4	2	2	7	7
FPE	150	0	0	0	130	132	133	129	135	134	132	134	131	130	130	130	130	126	125	128	129	20	11
FPE	160	0	0	0	12	16	26	37	45	53	54	52	49	45	43	41	40	78	70	63	52	4	4
FPE	170	200	200	200	169	9	0	3	10	0	0	0	0	1	0	1	1	0	2	0	0	4	4
FPE	180	200	200	200	187	10	0	0	0	0	1	0	0	2	0	0	0	0	0	0	0	4	4
FPE	200	0	0	0	6	8	16	24	33	45	53	106	107	106	101	99	93	82	74	64	58	10	5
FPE	210	0	0	0	128	128	126	128	122	124	127	126	125	123	121	115	121	106	110	115	117	20	10
FPE	220	200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
FPE	244	9	17	26	32	36	35	38	30	34	37	37	45	45	48	45	45	75	66	56	44	4	4
FPE	245	200	200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2
FPE	246	200	200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2
FPE	247	200	200	200	186	9	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	4	4
FPE	250	0	0	0	190	185	186	188	188	189	189	189	192	184	187	188	191	187	187	189	192	20	16
FPE	260	0	0	0	183	181	180	182	185	185	185	186	183	181	180	183	181	184	187	191	193	20	16
FPE	270	0	0	0	11	25	32	41	40	45	51	53	57	46	50	46	45	83	63	58	49	4	4

AVERAGE RESOURCES UTILIZED IN 200 SCHEDULES

INTERVAL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A WATTS	1203	635	666	7458	7527	7511	7505	7586	7595	7583	7600	7582	7629	7640	7651	7628	7602	7564	7562	7571
KW-HRS	7093	695	777	26831	27468	27776	27764	28894	29301	23389	30795	30600	30315	30736	30666	30484	30052	29580	29560	29335
BIT RT	70	67	84	58009	57857	57228	57338	58117	58388	58037	57569	57834	58502	59022	59554	58848	58408	58731	58633	59136
MAN HRS	8231	6920	5805	14486	14272	14305	14335	14085	13970	13936	13929	13806	13333	13942	13982	13890	14095	14192	14127	14030
SKILL 1	510	30	0	1128	1216	1293	1354	1395	1422	1431	1376	1386	1420	1438	1418	1414	1580	1511	1468	1412
SKILL 2	0	0	0	843	854	855	846	859	858	851	849	861	338	842	841	842	839	841	842	849
SKILL 3	0	0	0	694	699	698	686	696	696	692	693	697	681	676	682	680	676	680	691	693
SKILL 4	1338	1338	1338	1329	1390	1364	1357	1455	1425	1418	1412	1381	1366	1394	1397	1403	1399	1414	1429	1434
SKILL 5	1500	1500	1500	1613	1661	1636	1635	1486	1448	1435	1425	1394	1381	1408	1414	1416	1412	1428	1440	1447
SKILL 6	2	4	5	976	1049	1033	1033	1104	1088	1065	1065	1051	1367	1075	1107	1083	1073	1079	1085	1099
SKILL 7	2046	1206	1183	2238	1657	1680	1709	1504	1501	1516	1603	1600	1655	1648	1632	1610	1628	1610	1558	1523
SKILL 8	459	466	403	1980	1839	1884	1866	1945	1967	2009	1997	1997	1972	1987	1985	1951	2027	2140	2091	2026
SKILL 9	2376	2376	2376	3685	3907	3863	3848	3641	3565	3520	3509	3438	3423	3473	3506	3491	3460	3489	3523	3549
S WT UP	1136	1120	1026	8643	8529	9008	9465	9259	9391	9351	8947	9080	8731	8654	8607	8692	10110	9733	9402	9043
S VOL UP	24	25	25	573	584	586	592	592	598	598	591	592	585	585	589	586	612	607	600	600
RET WT	8759	5167	1372	16340	13777	13779	16302	18337	17438	27074	17161	16537	15733	16607	18232	20536	18550	18437	16911	203049
RET VOL	150	222	52	746	551	600	1668	2256	2104	3957	1926	2036	1367	1768	2198	3101	2413	2980	1995	62365
E WT UP	16284	82	249	176541	12901	5963	4660	7514	6048	4048	9350	4278	4409	4664	3641	4330	13786	1115	1158	464
E VOL UP	785	13	22	56220	4203	2339	1727	2654	2353	1539	3155	1689	1459	1635	1304	1549	5273	291	275	182
SS VOL	809	702	534	1310	1244	1252	1273	1246	1265	1273	1267	1279	1269	1268	1258	1247	1338	1305	1268	1236
PC COMPL	2	4	6	10	14	17	21	25	29	33	36	40	45	49	53	57	61	65	69	73

AVERAGE COST PER YEAR

1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
.00	17.08	74.38	166.69	279.41	328.94	294.58	229.56	114.68	36.40
.03	17.08	91.46	258.05	537.46	866.40	1160.98	1390.55	1535.23	1541.63
1980	1981	1982	1983	1984	1985	1986	1987	TOTAL	
36.94	34.57	29.95	23.71	14.24	1.53	.15	.00	1682.72	
1578.57	1613.14	1643.09	1666.80	1681.04	1682.57	1682.72	1682.72		

FIGURE 2

MAXIMUM VALUE OF RESOURCES FOR 200 SCHEDULES

INTERVAL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A WATTS	1208	640	670	8000	8000	8000	8000	7998	7995	7998	7998	7998	7399	8000	8000	8000	8000	8000	8000	8000
KW-HRS	7116	720	798	41526	41226	41226	41220	41370	41304	41244	42390	42564	42774	42774	42690	42690	42690	41442	41436	41436
BIT RT	70	67	84	79603	79604	79649	79651	79637	79655	73655	79655	79614	79513	73611	79611	79653	79658	79614	79614	79610
MAN HRS	8592	7266	7134	16380	16380	16380	16380	16368	16380	16380	16380	16380	16374	16380	16380	16368	16380	16380	16380	16380
SKILL 1	510	30	0	1800	1974	2238	2298	2064	2136	2178	2196	2178	2460	2460	2442	2184	2460	2382	2322	2154
SKILL 2	0	0	0	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092
SKILL 3	0	0	0	948	948	948	948	948	948	949	948	948	948	948	948	948	948	948	948	948
SKILL 4	1338	1338	1338	1788	1788	1788	1788	1746	1746	1746	1746	1746	1746	1746	1746	1788	1746	1746	1746	1746
SKILL 5	1500	1500	1500	2172	2172	2172	2112	2112	2112	2112	2112	2112	2112	2112	2112	1866	1806	1806	2112	1806
SKILL 6	42	42	42	1644	1644	1644	1644	1644	1644	1644	1644	1644	1644	1644	1644	1644	1644	1644	1644	1644
SKILL 7	2184	1338	1308	3192	2634	2454	2568	3162	2448	2448	2406	2586	2334	2316	2304	3210	2712	2688	2640	2496
SKILL 8	642	642	570	3864	3600	3822	3822	3804	3600	3642	3498	3606	3642	3672	3462	3432	3612	3720	3684	3684
SKILL 9	2375	2376	2376	5274	5274	5274	5274	5274	5274	4734	4734	4734	4734	5274	5274	4734	4734	4734	4734	4734
S WT UP	1182	1164	1068	16602	16404	16518	16908	17124	16764	16764	16374	16074	17718	17718	17052	16632	17352	17352	17238	16338
S VOL UP	39	33	30	900	900	906	930	924	918	918	906	900	942	942	924	906	942	936	918	906
RET WT	8908	5310	4882	62819	69373	59432	59993	77840	58724	98002	92432	67309	72212	74608	71108	90540	77923	120672	72868	272740
RET VOL	155	227	419	11102	9919	9957	11613	17993	17986	26087	17623	21779	17998	20686	27040	17986	21689	35960	24441	82009
E WT UP	18242	2050	22072	43542	97546	62348	72252	64991	51001	58711	73079	39104	51162	72252	58491	42474	72252	51001	51001	40424
E VOL UP	1087	316	324	77586	31794	25611	18723	28084	17539	24374	24427	17486	21217	18723	12881	17499	18723	10609	10598	10598
SS VOL	1117	997	814	1799	1744	1913	1913	1872	1838	1804	1812	1834	1815	1858	1839	1818	1968	1968	1829	1822
PC COMPL	2	5	7	12	15	20	25	30	33	35	43	47	51	54	58	62	66	70	73	78

1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
.03	18.15	86.62	187.32	336.45	364.92	343.14	294.43	169.58	89.59
.00	18.15	104.32	291.64	592.40	947.76	1283.09	1560.70	1708.87	1760.50
1980	1981	1982	1983	1984	1985	1986	1987	TOTAL	
98.25	95.59	108.40	97.82	65.40	28.00	10.94	.00	1830.84	
1904.45	1821.29	1828.74	1830.65	1830.84	1830.84	1830.84	1830.84		

FIGURE 3

REQUIRED MANPOWER PER MONTH

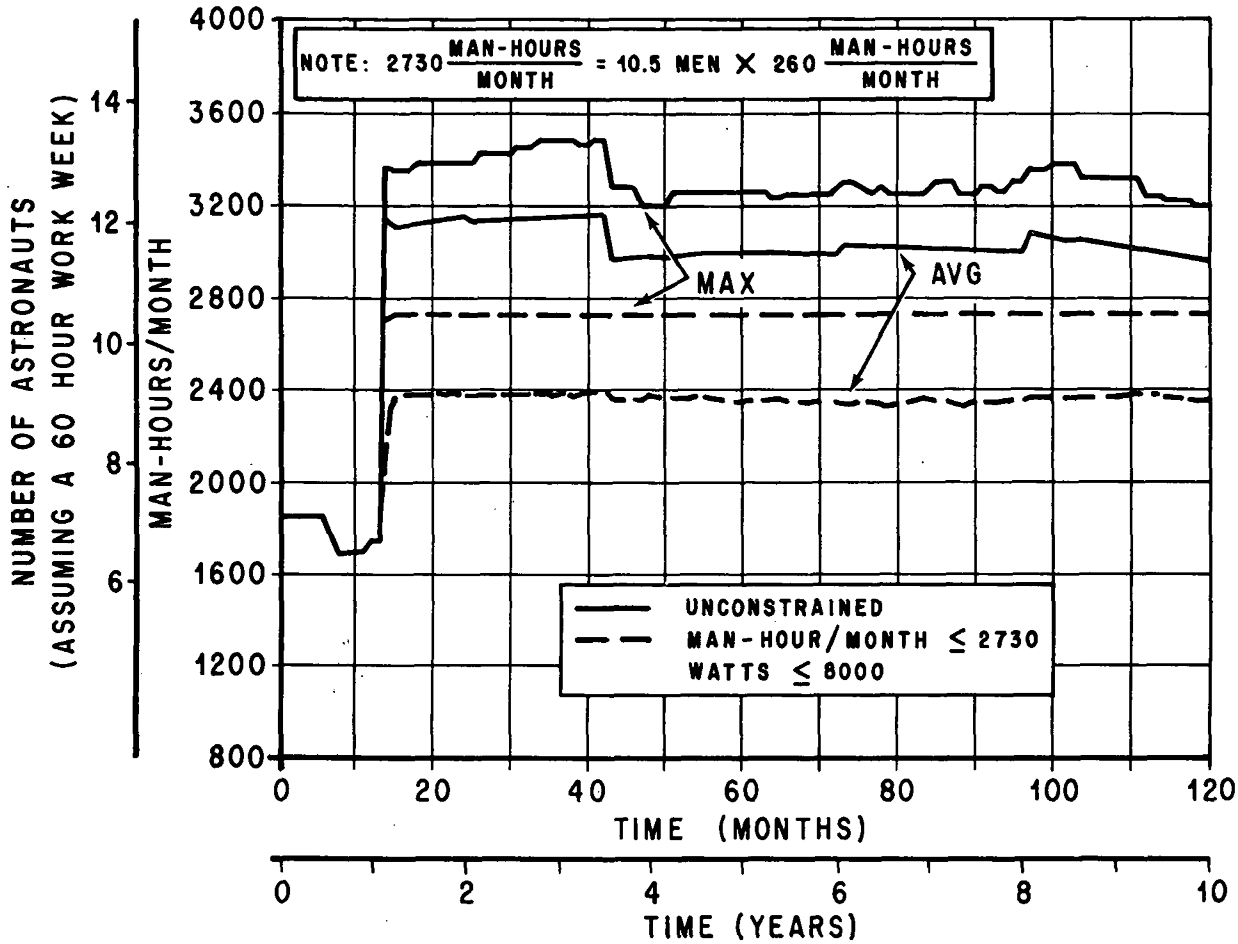


FIGURE 4

AVERAGE MANPOWER REQUIRED OF EACH SKILL PER MONTH

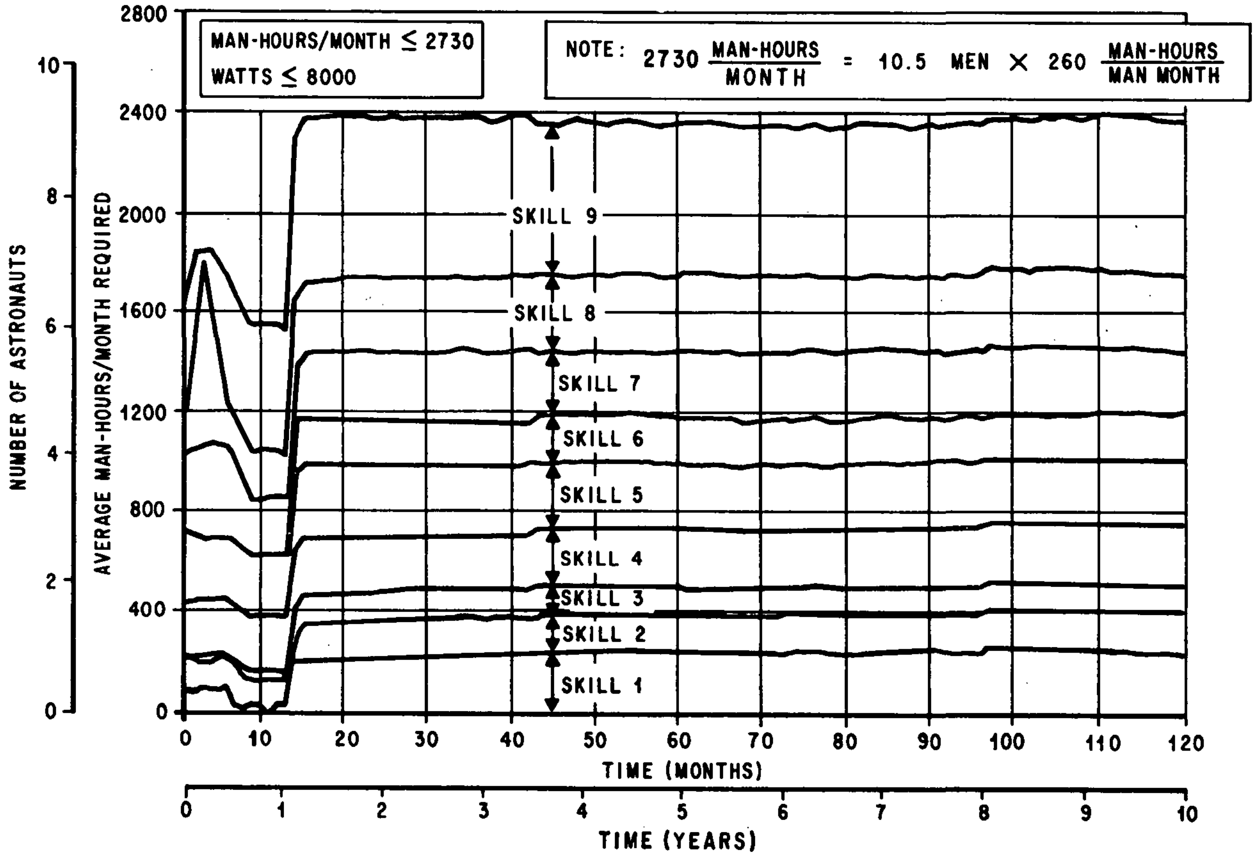


FIGURE 5

AVERAGE ELECTRICAL POWER REQUIRED

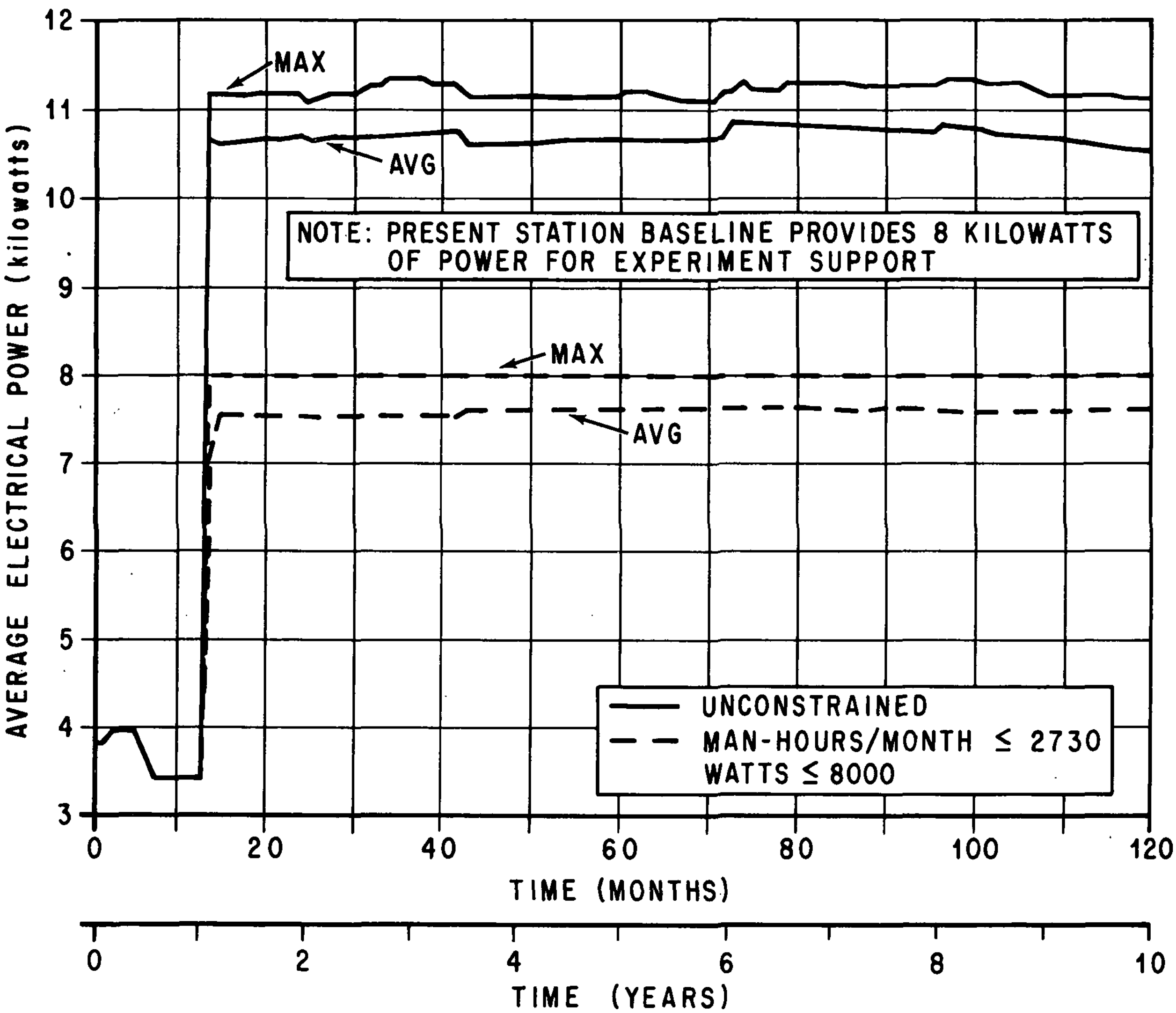


FIGURE 6

CUMULATIVE PERCENT OF BLUE BOOK PROGRAM COMPLETED

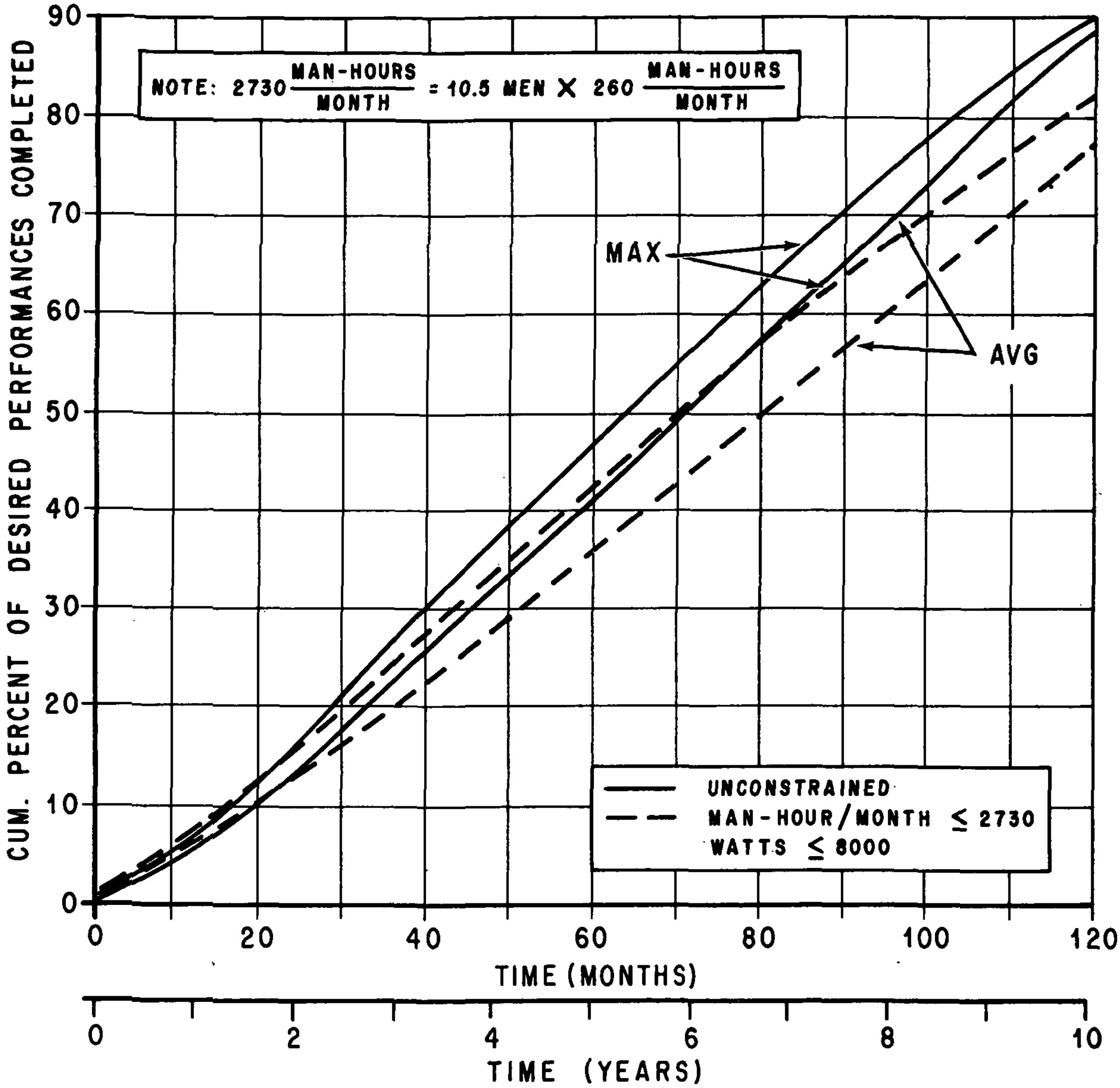


FIGURE 7

STATION STORAGE VOLUME ASSUMING EXPERIMENT ARE DEORBITED AFTER COMPLETION

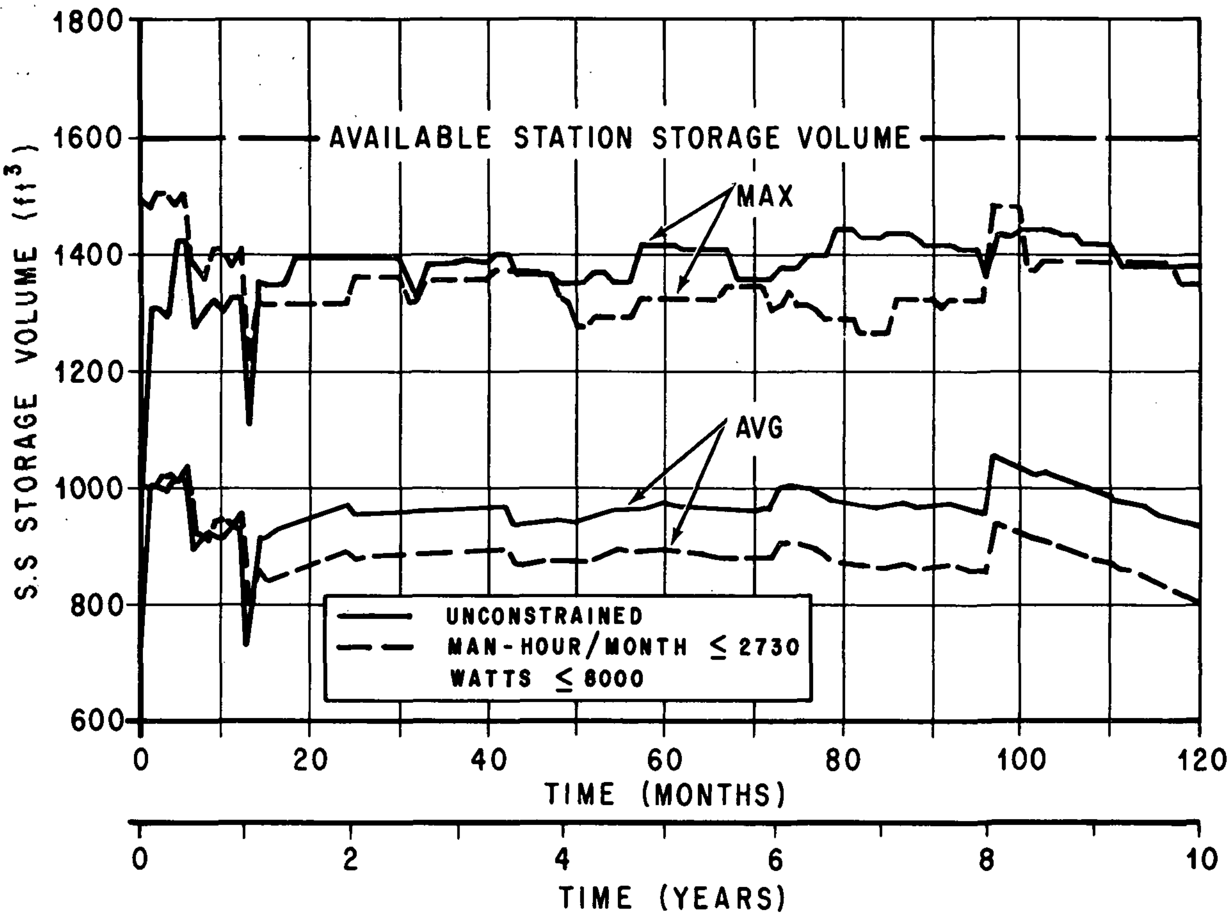


FIGURE 8

CUMULATIVE COST OF EXPERIMENT PROGRAM

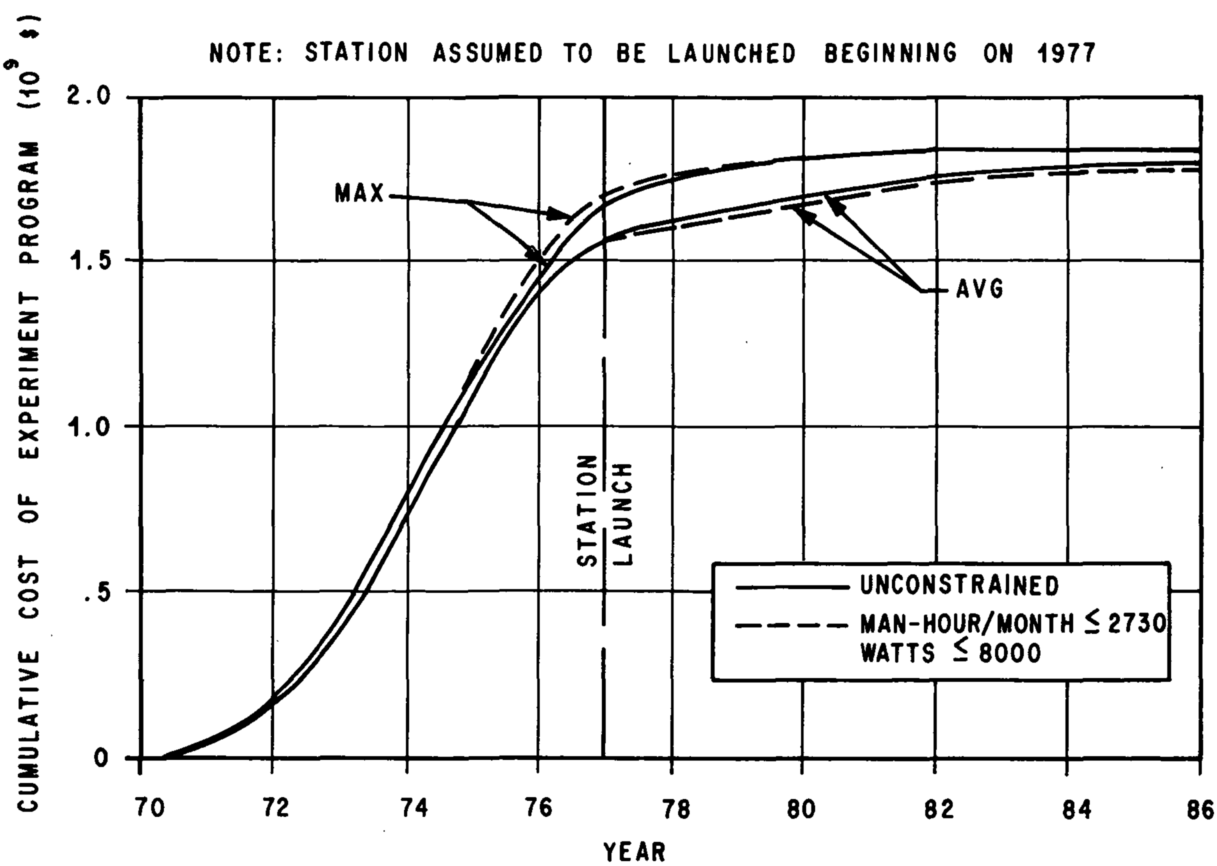


FIGURE 9

BITS PER DAY GENERATED

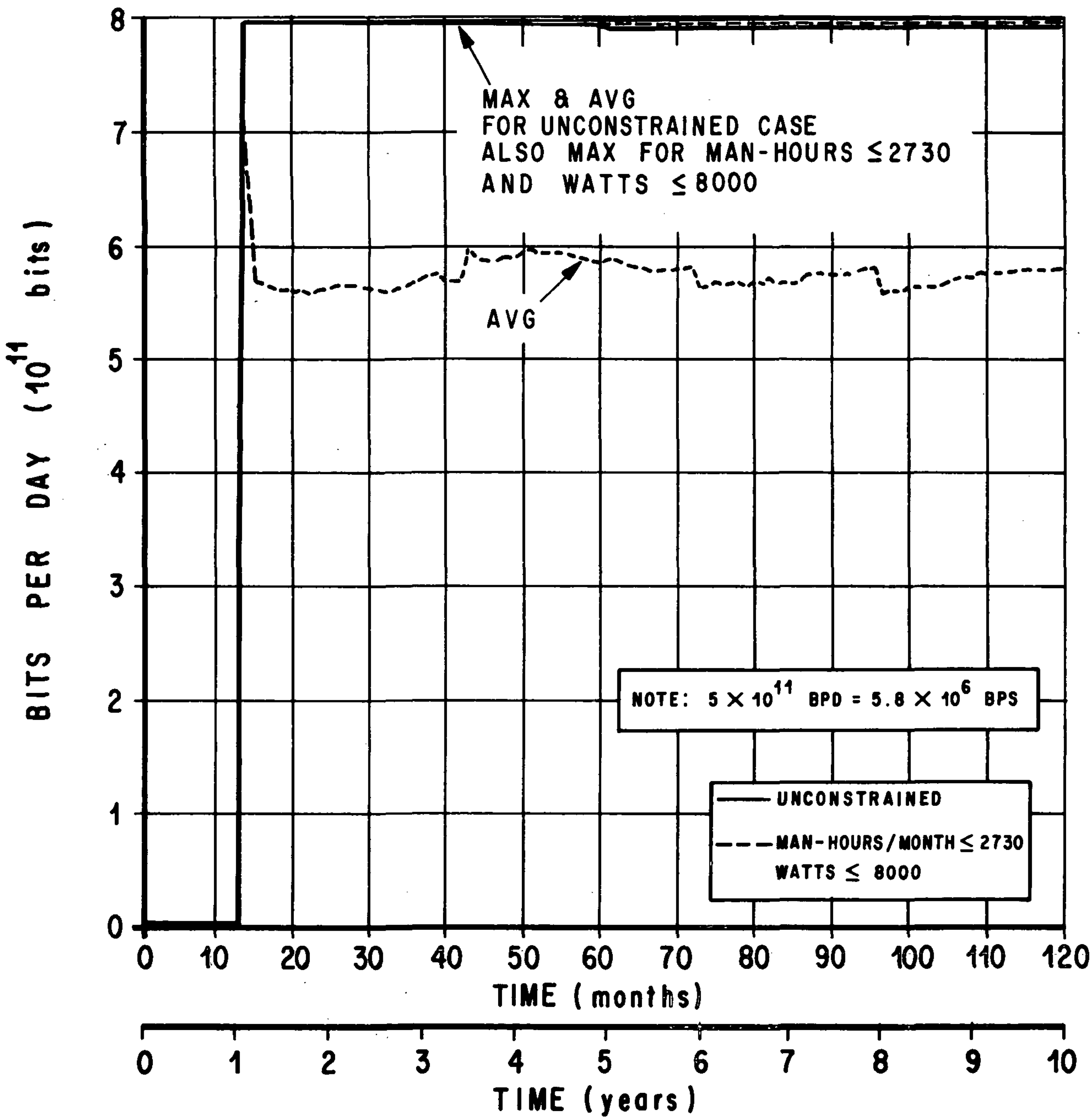


FIGURE 10

SENSITIVITY OF MEAN PERCENT OF BLUE BOOK PROGRAM COMPLETED TO SPACE STATION MANPOWER AND ELECTRICAL POWER

NOTE: EACH DATA POINT BASED ON A SAMPLE OF 200 RANDOM CANDIDATE EXPERIMENT PROGRAMS FROM BLUE BOOK

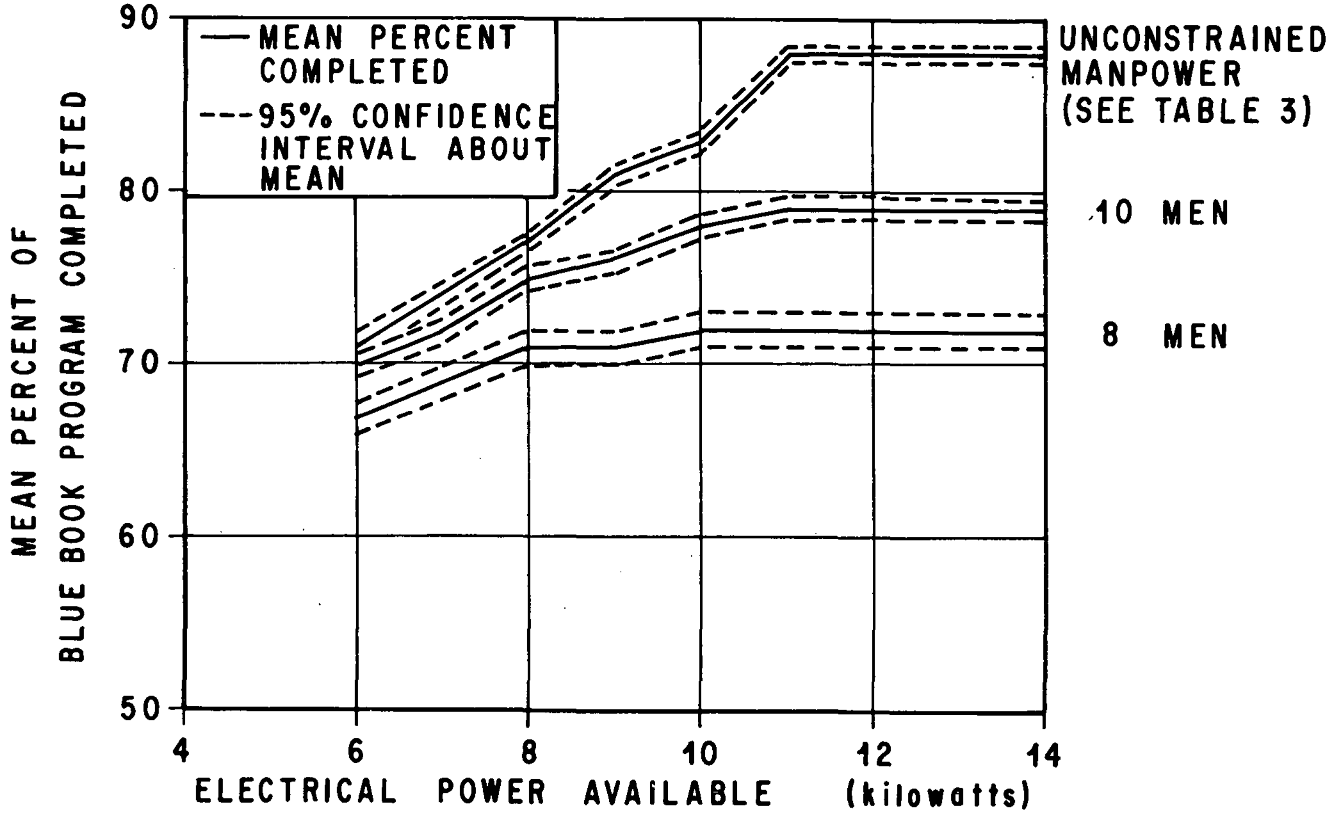


FIGURE 11

SENSITIVITY OF MEAN AND MAXIMUM PERCENT OF BLUE BOOK PROGRAM COMPLETED TO SPACE STATION MANPOWER AND ELECTRICAL POWER

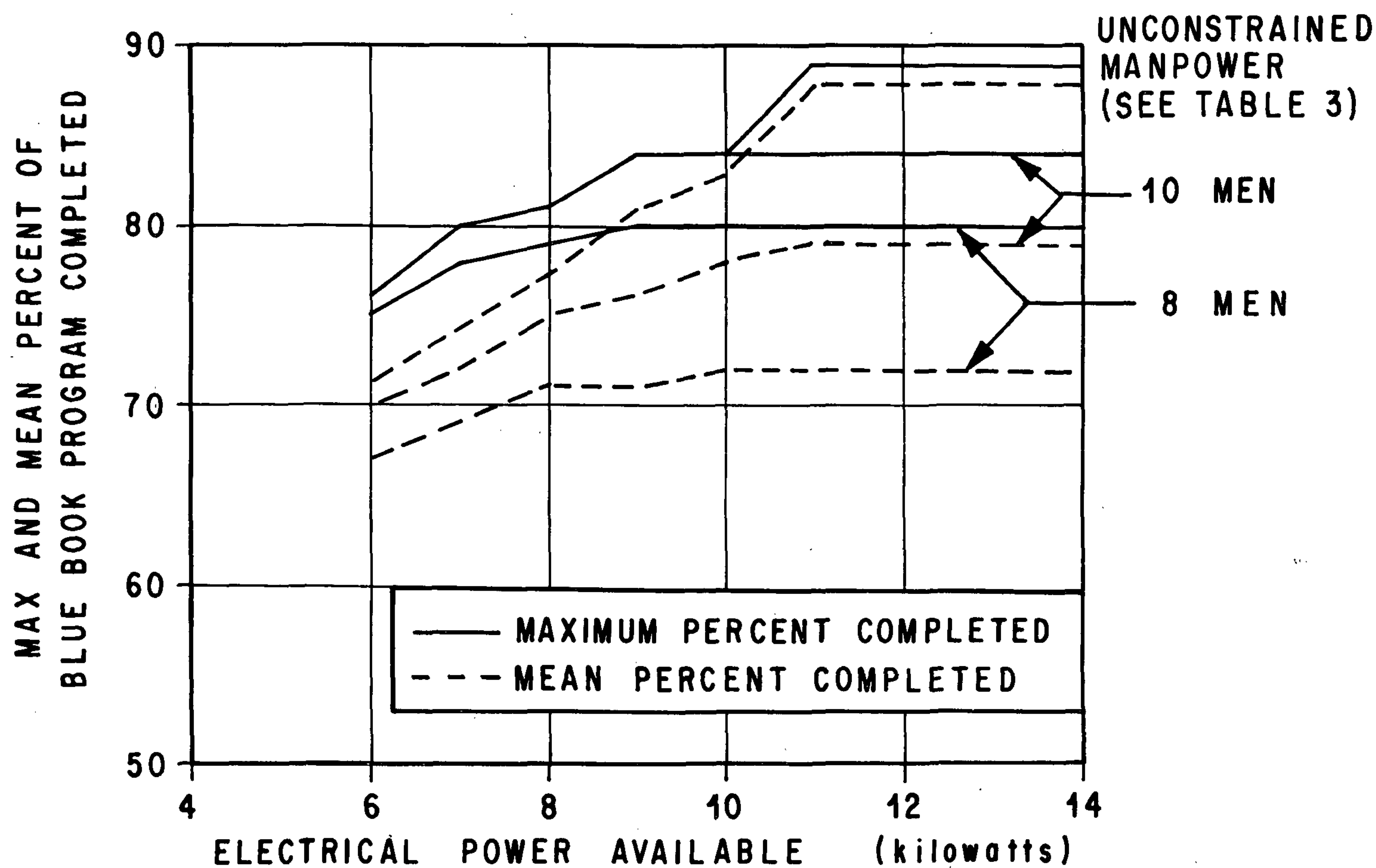


FIGURE 12

SENSITIVITY OF FPE DEVELOPMENT COST TO SPACE STATION MANPOWER AND ELECTRICAL POWER

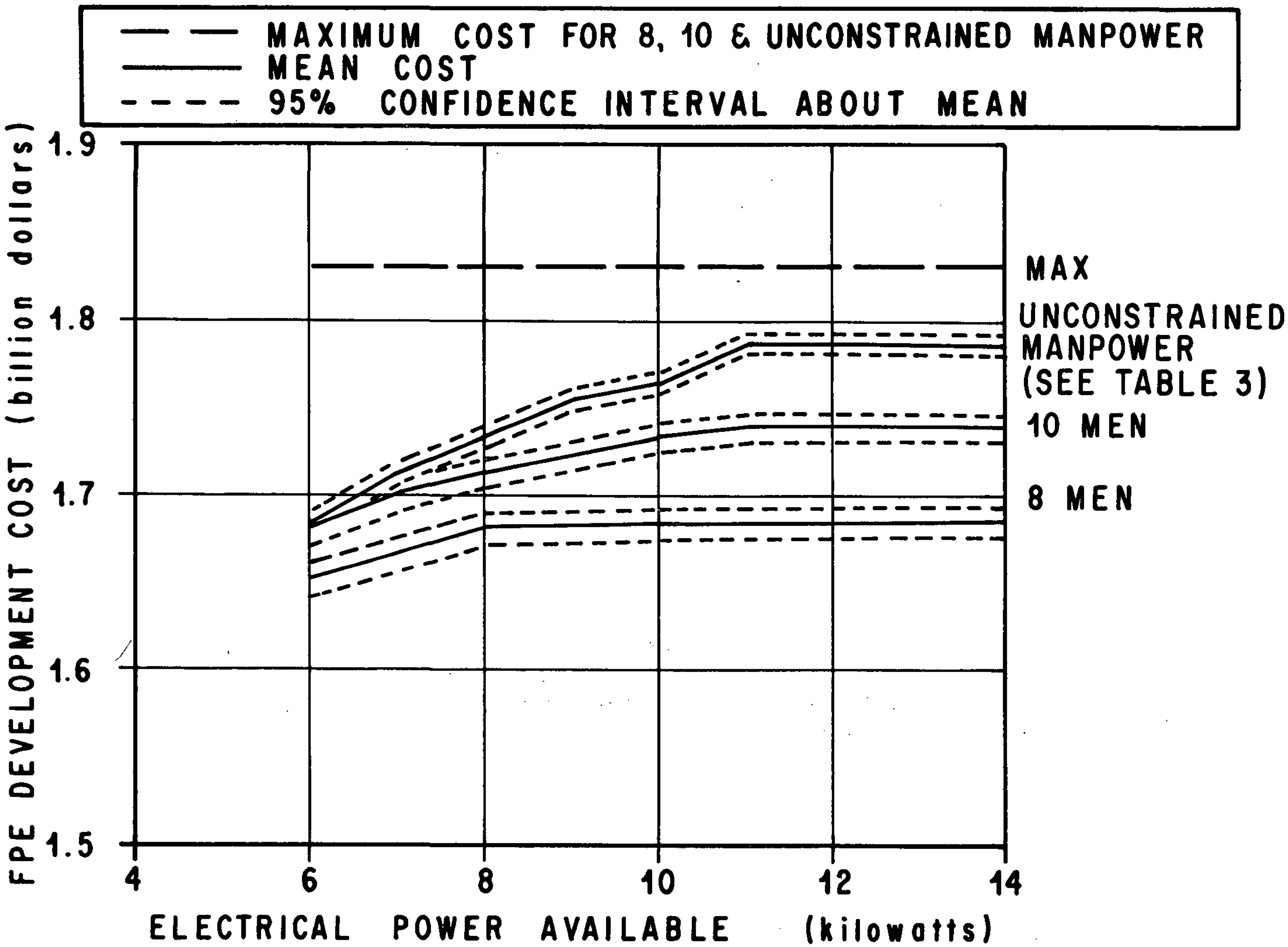


FIGURE 13

SENSITIVITY OF SPACE STATION DATA HANDLING REQUIREMENT TO SPACE STATION MANPOWER AND ELECTRICAL POWER

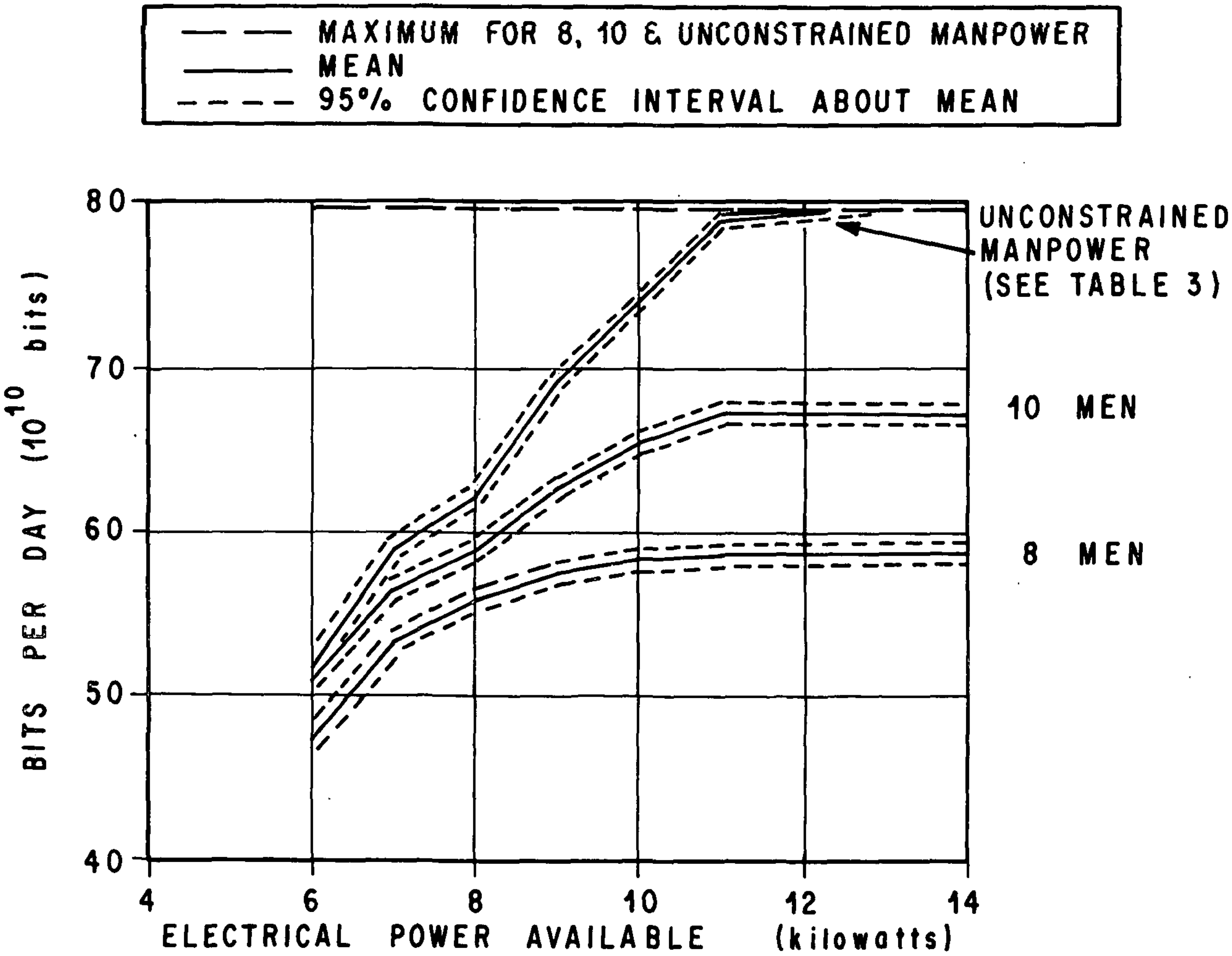


FIGURE 14

SENSITIVITY OF SPACE STATION STORAGE VOLUME TO SPACE STATION MANPOWER AND ELECTRICAL POWER

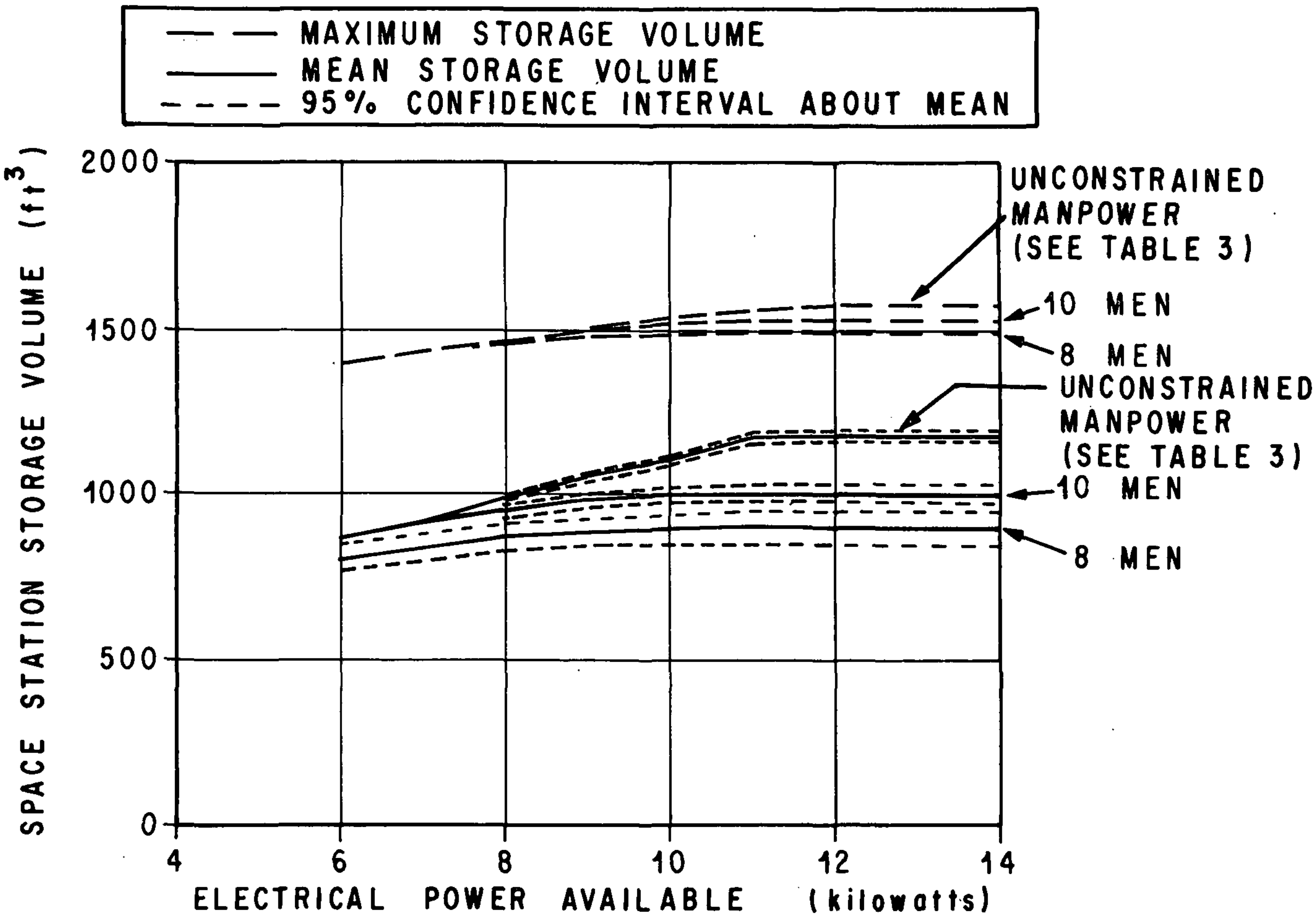


FIGURE 15

MEAN PERCENT OF BLUE BOOK PROGRAM COMPLETED

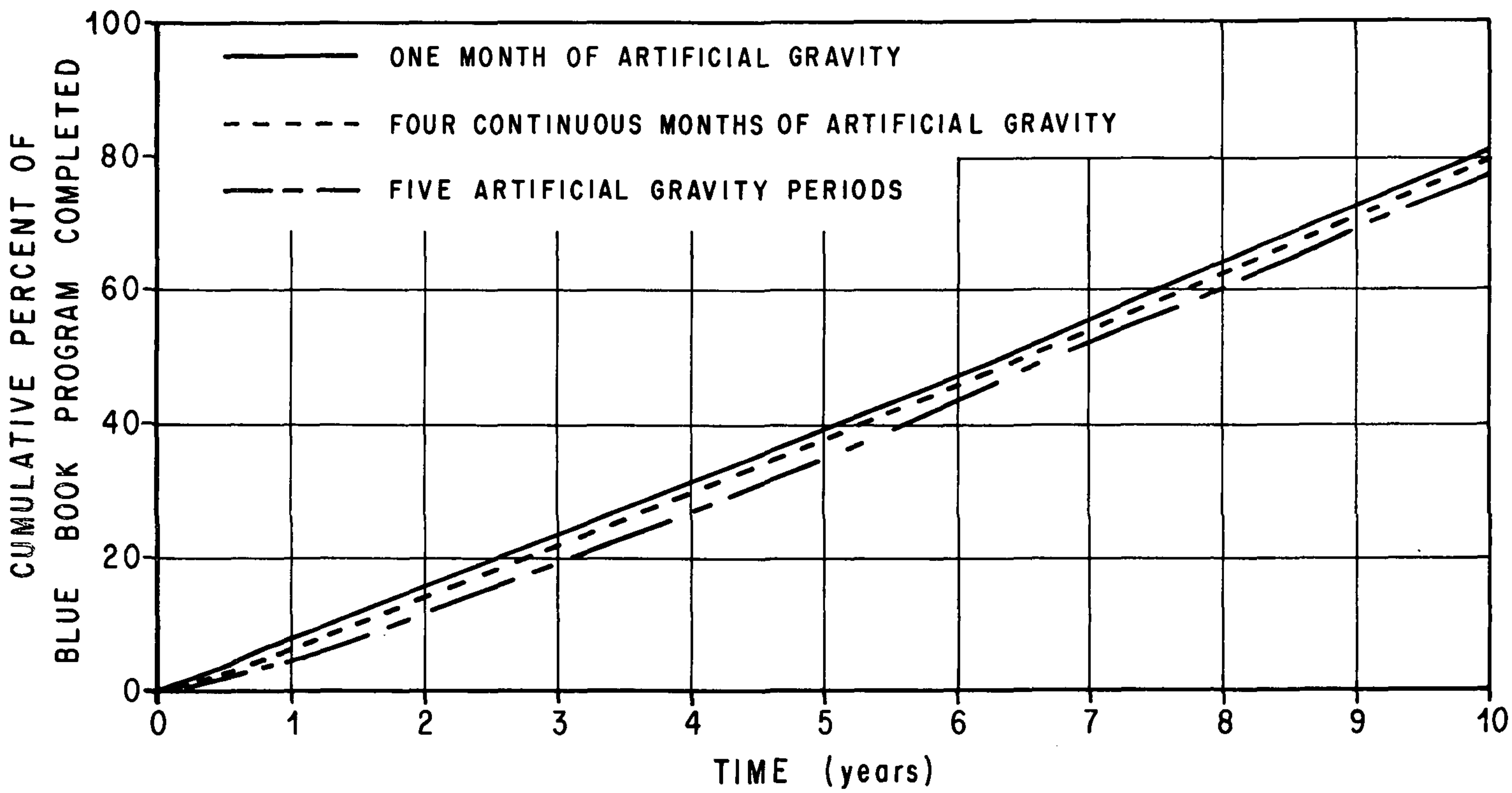


FIGURE 16

MAXIMUM PERCENT OF BLUE BOOK PROGRAM COMPLETED

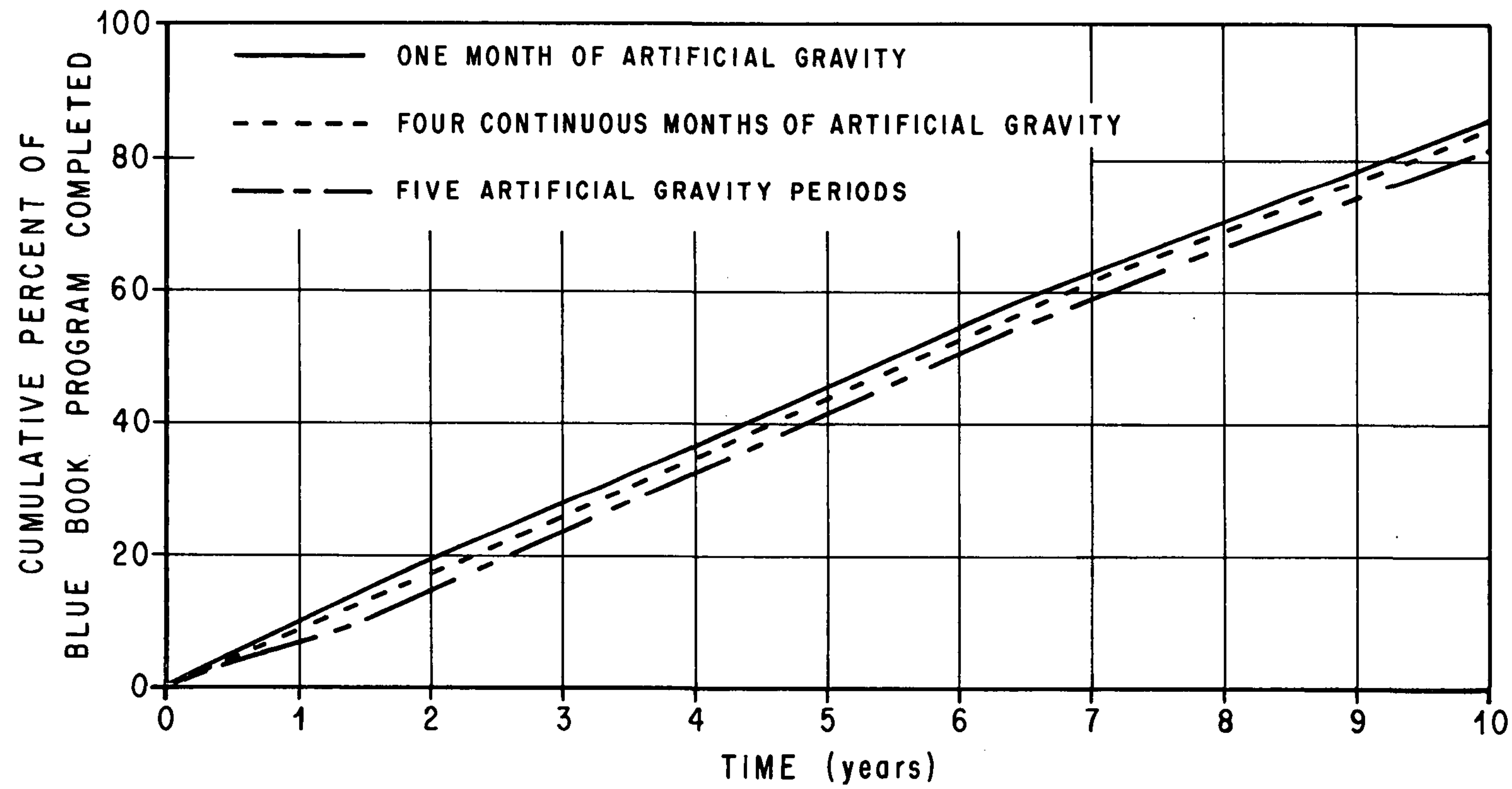


FIGURE 17

LOGISTICS WEIGHT TO ORBIT REQUIRED EACH THREE MONTHS

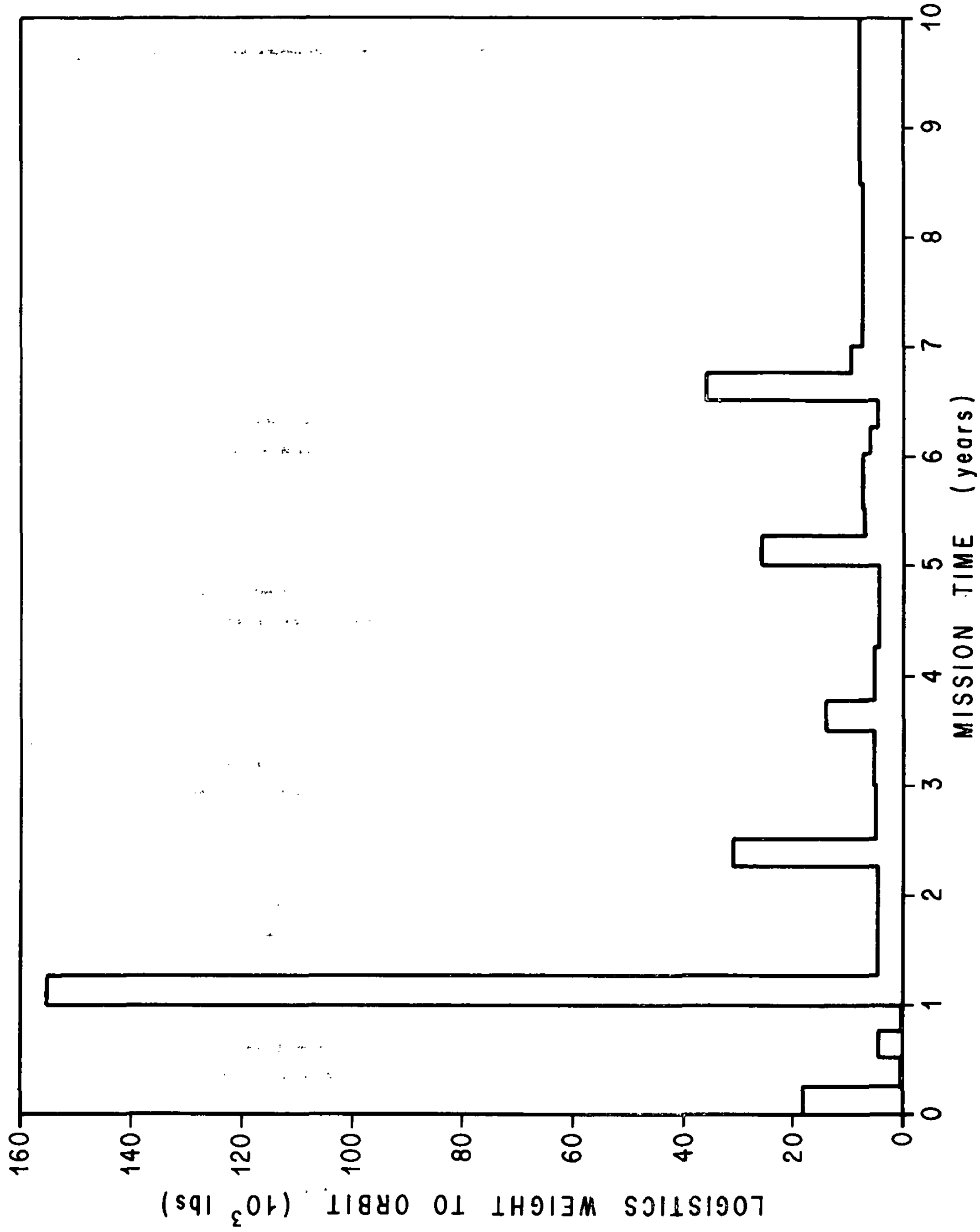


FIGURE 18

LOGISTICS VOLUME TO ORBIT REQUIRED EACH THREE MONTHS

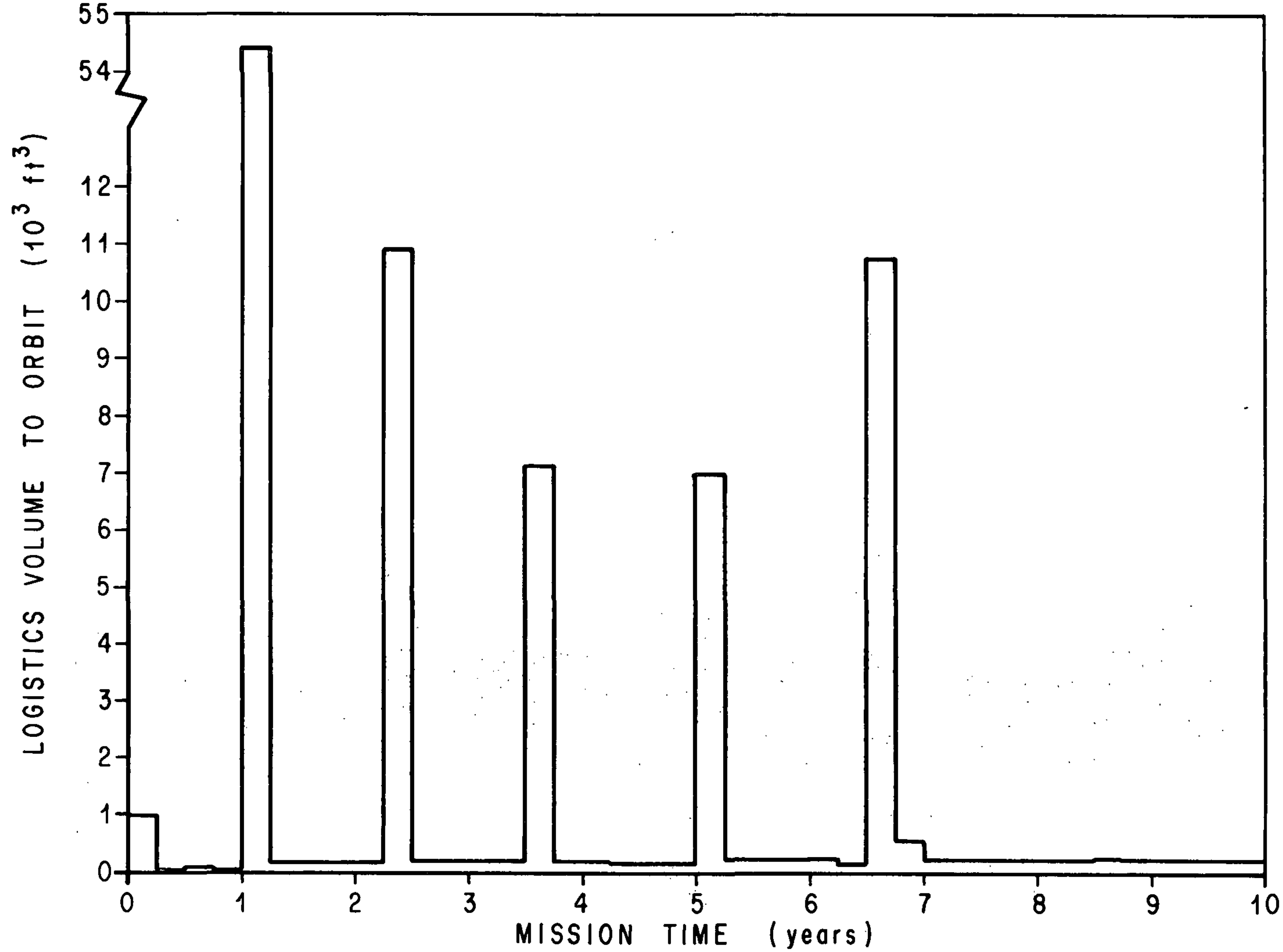


FIGURE 19

LOGISTICS WEIGHT TO BE RETURNED FROM ORBIT EACH THREE MONTHS

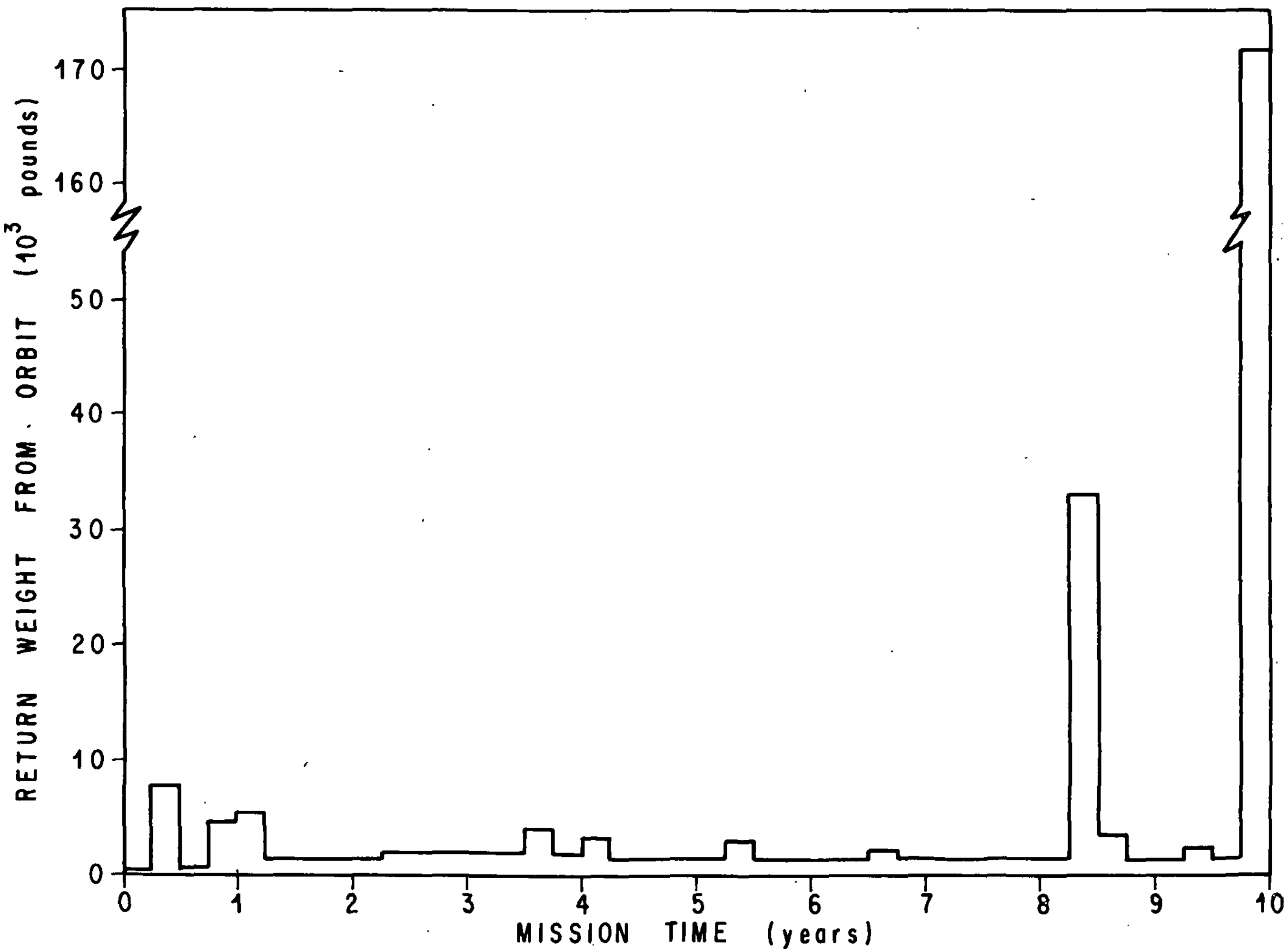


FIGURE 20

LOGISTICS VOLUME TO BE RETURNED FROM ORBIT EACH THREE MONTHS

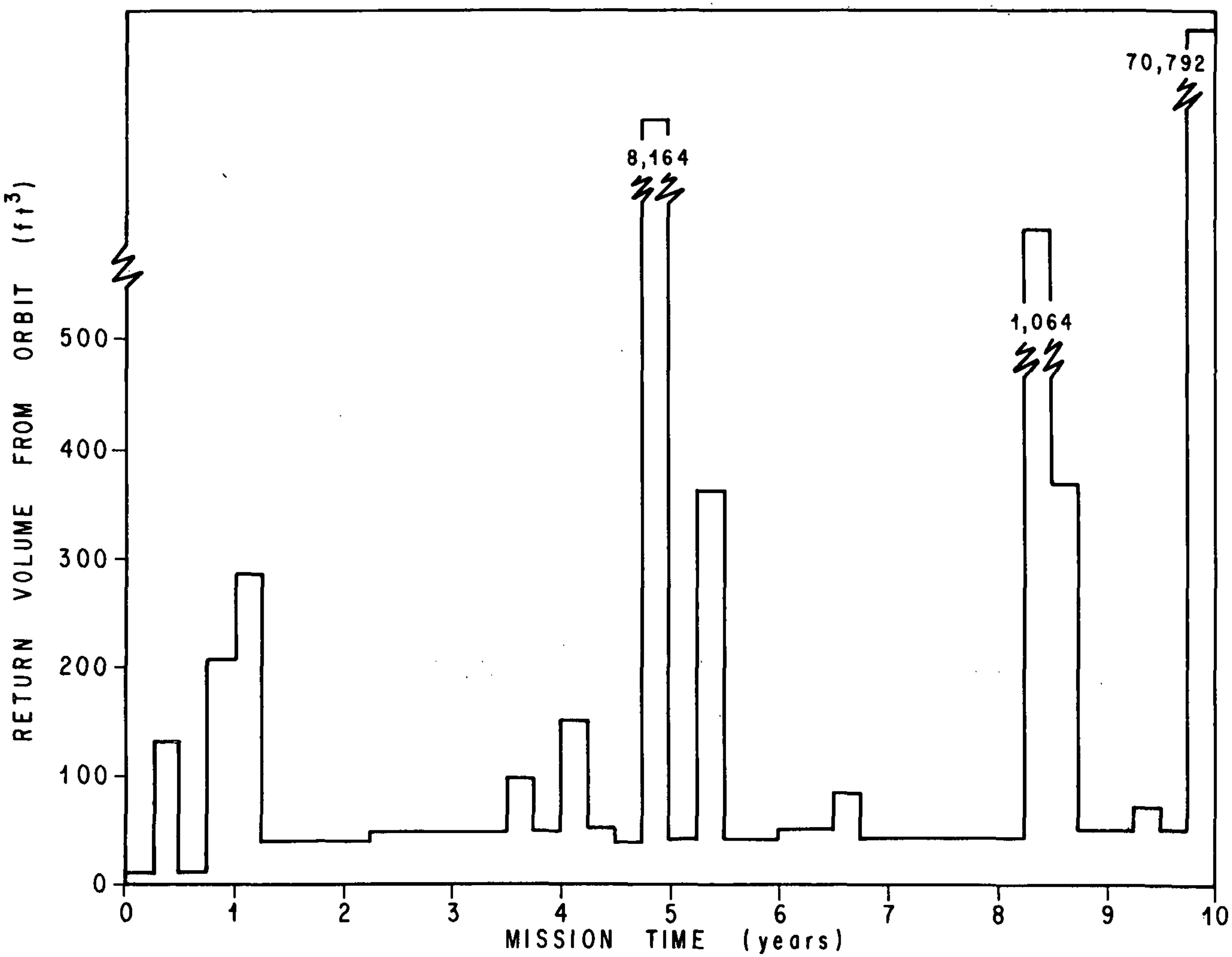


FIGURE 21

APPENDIX A

Sampling Theory

This appendix, prepared by E. H. Kelley and W. T. Pease of the Northrop Corporation, is used to determine the sample size (number of schedules) required to achieve desired levels of confidence and probability.

Let S_1, S_2, ..., denote the schedules in the set of all possible randomly generated schedules, and let f_i denote the ith payoff function (i.e., parameter) defined on all possible schedules. The sequence of values of f_i, given by $f_i(S_1)$, $f_i(S_2)$, ..., can be considered as a sequence of independent random variables with an unknown distribution, F. Then $F_i(x)$ is the probability that a randomly generated schedule (see Figure A-1) will have an f_i value smaller than x; i.e.,

$$F_i(x) = P_r\,[f_i(S) < x] = \int_o^x y_i(x)\,dx,$$

where S is an arbitrary random schedule.

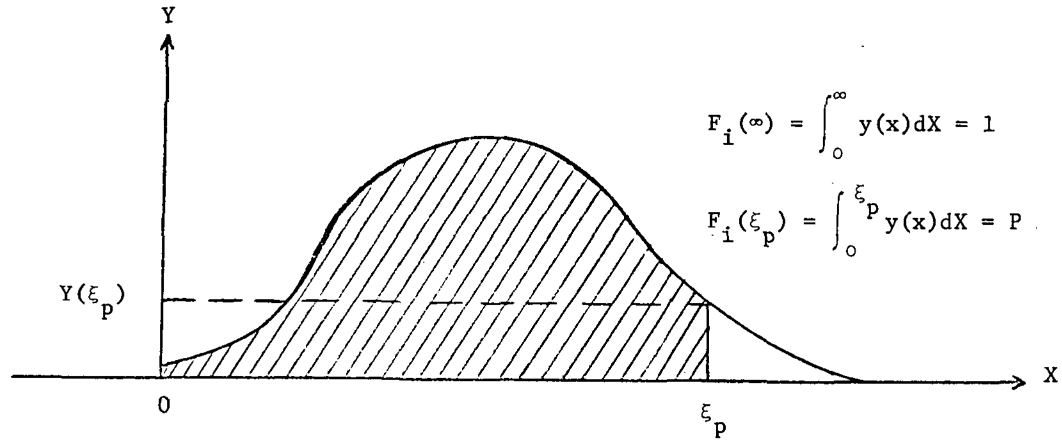
Let ξ_p be the p-percentile of the unknown distribution F_i; i.e., p is the number such that

$$F_i(\xi_p) = P_r[f_i(S) < \xi_p] = p = \int_o^{\xi_p} y_i(x)\,dx, \quad 0 \leq p \leq 1. \tag{A-1}$$

Suppose that the outcome of an f_i value greater than or equal to ξ_p from a given schedule be designated as a success and the outcome of an f_i value less than ξ_p be designated as a failure. Hence, by equation (A-1), the probability of a failure for any random schedule is given by p, and conversely the probability of a success is given by (1 - p).

If a finite number of schedules, N, are generated, the probability that at least one of these N schedules will have an f_i value greater than or equal to ξ_p may be expressed as the probability of at least one success in N independent trials, and this probability may be denoted by

$$P_r[\text{at least one } f_i(S_k) \geq \xi_p], \quad k = 1, 2, \ldots, N.$$



Note: The probability, $F_i(\infty) = P_r[f_i(S) < \infty] = 1$, that a random f_i value will lie in the interval $[o, \infty]$ is represented by the total area under the curve from 0 to ∞.

The probability, $F_i(\xi_p) = P_r[f_i(S) < \xi_p] = p$, that a random f_i value will lie in the interval $[0, \xi_p]$ is represented by the shaded area under the curve from 0 to ξ_p.

Figure A-1. DISTRIBUTION CURVE FOR THE SCHEDULE PARAMETER f_i

By Bernoulli's Theorem*, the probability of exactly j failures and (n-j) successes in n independent trials is given by the expression

$$P_r = \frac{n!}{j!(n-j)!} p^j (1-p)^{n-j}. \tag{A-2}$$

Since an outcome of at least one success in n trials includes all possible outcomes except that of exactly n failures, the probability of at least one success is given by

$$1 - [P_r(\text{n failures in n trials})].$$

Thus, the probability of at least one f_i value greater than or equal to ξ_p in the N random schedules generated may be expressed as

$$P_r[\text{at least one } f_i(S_k) \geqq \xi_p] = 1 - [P_r(\text{all N } f_i(S_k) < \xi)],$$

$$k = 1, 2, \ldots, N. \tag{A-3}$$

Replacing n by N, and j by N in expression (A-2), we have

$$P_r[\text{all N } f_i(S_k) < \xi_p] = \frac{N!}{N!(N-N)!} p^N (1-p)^{N-N} = p^N$$

$$k = 1, 2, \ldots, N,$$

and substituting p^N in equation (A-3) we have

$$P_r[\text{at least one } f_i(S_k) \geqq \xi_p] = 1-p^N, \quad k = 1, 2, \ldots, N. \tag{A-4}$$

The value of p is sometimes called the confidence interval.

---

*Coolidge, J. L., An Introduction to Mathematical Probability, Dover Publications, Inc., New York, N. Y., 1962, p. 32.

As an example of the application of equation (A-4), suppose it is desired to know the number, N, of schedules required to have the probability be 0.95 that the maximum (minimum) value for the f_i parameter in the sample $S_1, \ldots, S_N$ of N schedules is larger (smaller) than 99 percent of all possible values. Then the preceding equation becomes

$$0.95 = 1 - (0.99)^N.$$

In general, the exact solution of this equation will not yield an integer value for N; therefore, the equation is solved for the smallest value for N for which the probability is at least 0.95; i.e., the smallest integer N is sought for which the inequality given by

$$0.95 \leqq 1 - (0.99)^N$$

holds. The value of N is found to be N = 296.

Figure A-2 is a graph of P_r as a function of N for values of p of 0.90, 0.95, and 0.99. Figure A-3 is a plot of p as a function of N for values of P_r of 0.90, 0.95, and 0.99. Using these graphs, the number of schedules which must be generated to achieve the desired p and P_r values can be readily obtained.

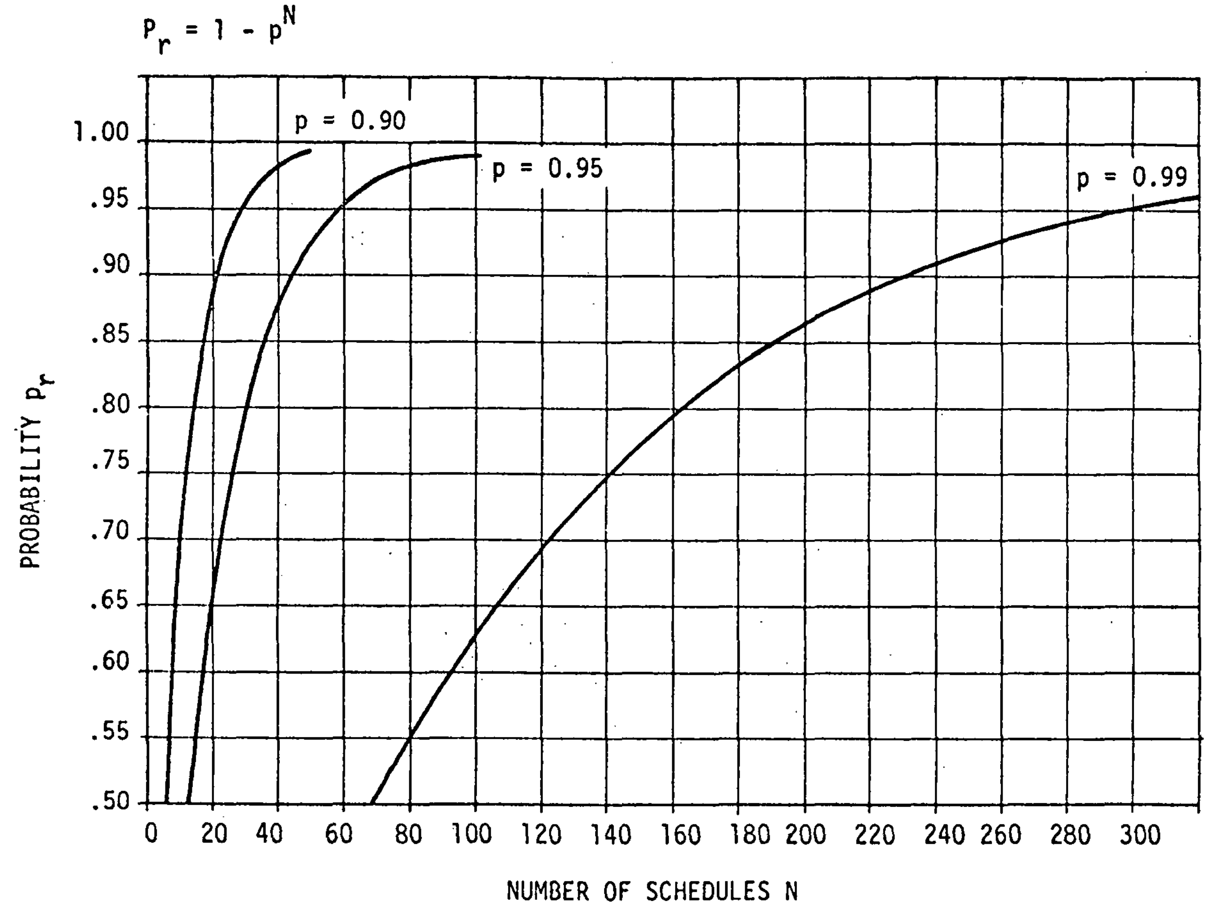


Figure A-2. PROBABILITY AS A FUNCTION OF THE NUMBER OF SCHEDULES

$$p = \sqrt[N]{1 - P_r}$$

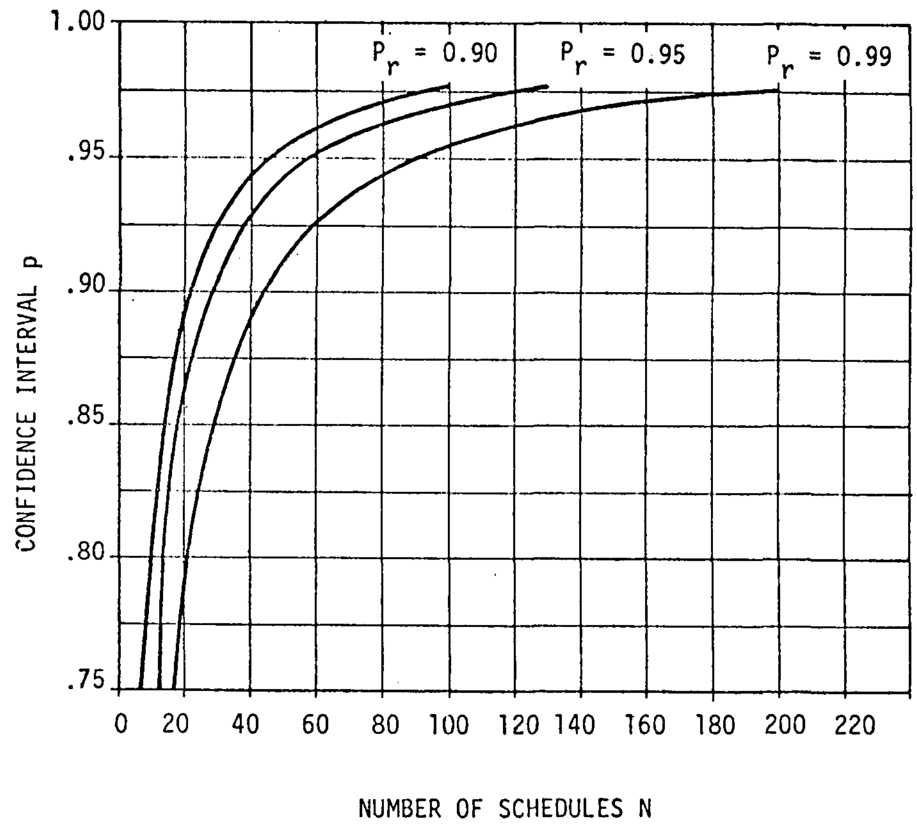


Figure A-3. CONFIDENCE INTERVAL AS A FUNCTION OF NUMBER OF SCHEDULES

APPENDIX B

Calculation of Confidence Limits for Mean Values

This appendix was prepared by R. M. Harnett of the Northrop Corporation, Electro-Mechanical Division.

In developing the confidence limits of a mean value ($\bar{x}$) of a sample (x_i) of size n taken from an unknown parent population, the following theorem (Central Limit Theorem) is used: The distribution of all possible values of $\bar{x}$ approaches normality as n becomes relatively large (see ref. 3, p. 133; ref. 4, p. 90; ref. 5, p. 211; ref. 6, p. 165; ref. 7, p. 40; ref. 8, p. 295; and ref. 9, p. 229). Further, it can be shown that $\mu_{\bar{x}}$ (the expected value of $\bar{x}$) is equal to the mean of the parent population and that the variance of the distribution of values of $\bar{x}$ is given by

$$\sigma_{\bar{x}}^2 = \frac{1}{n^2} \sum_{i=1}^{n} \sigma^2 = \frac{\sigma^2}{n} ,$$

where

σ^2 = variance of parent population

and

n = size of sample from which $\bar{x}$ is computed.

The proofs of these follow:

(1) $E[\bar{x}] = \mu_{\bar{x}}$; $E[\bar{x}]$ = expected value of $\bar{x}$

$$E[\bar{x}] = E\left[\frac{x_1 + x_2 + \dots + x_n}{n}\right]$$

$$E[\bar{x}] = \frac{1}{n}\left[E(x_1) + E(x_2) + \dots + E(x_n)\right]$$

$$E[\bar{x}] = \frac{1}{n}\left[\mu + \mu + \dots + \mu\right]$$

$$E[\bar{x}] = \frac{1}{n}[n\mu]$$

$$E[\bar{x}] = \mu.$$

(2) $$\sigma^2_{\bar{x}} = V[\bar{x}]$$

$$\sigma^2_{\bar{x}} = V\left[\frac{x_1 + x_2 + \ldots + x_n}{n}\right]$$

$$\sigma^2_{\bar{x}} = \frac{1}{n^2} V[x_1 + x_2 + \ldots + x_n]$$

$$\sigma^2_{\bar{x}} = \frac{1}{n^2} [Vx_1 + Vx_2 + \ldots + Vx_n]$$

$$\sigma^2_{\bar{x}} = \frac{1}{n^2} [\sigma^2 + \sigma^2 + \ldots + \sigma^2]$$

$$\sigma^2_{\bar{x}} = \frac{1}{n^2} [n\sigma^2]$$

$$\sigma^2_{\bar{x}} = \frac{\sigma^2}{n} .$$

Hence, the variance of the parent population (σ^2) is required to calculate the variance of the means ($\sigma^2_{\bar{x}}$).

Assuming that σ^2 is known from previous experience with the population, then the standard normal test statistic (Z) could be determined from

$$Z_o = \frac{\bar{x} - \mu}{\sigma/\sqrt{n}},$$

where $Z \sim N(0,1)$*. The test statistic Z_o is a random variable since it is a function of the random variable $\bar{x}$. The mean of $Z_o = 0$, or $E(Z_o) = 0$,

*$Z \sim N(0,1)$ is interpreted: Z is distributed normally with a mean of 0 and a standard deviation of 1. This is read, "Z is normal, zero one."

since

$$E[Z_o] = E\left[\frac{\bar{x} - \mu}{\sigma/\sqrt{n}}\right]$$

$$E[Z_o] = \frac{\sqrt{n}}{\sigma} E[\bar{x} - \mu]$$

$$E[Z_o] = \frac{\sqrt{n}}{\sigma} [E[\bar{x}] - E[\mu]]$$

$$E[Z_o] = \frac{\sqrt{n}}{\sigma} [\mu - \mu]$$

$$E[Z_o] = \frac{\sqrt{n}}{\sigma} [0]$$

$$E[Z_o] = 0.$$

The variance of $Z_o = 1$, or $V(Z_o) = 1$, since

$$V[Z_o] = V\left[\frac{\bar{x} - \mu}{\sigma/\sqrt{n}}\right]$$

$$V[Z_o] = V\left[\frac{\sqrt{n}}{\sigma} \cdot (\bar{x} - \mu)\right]$$

$$V[Z_o] = \frac{n}{\sigma^2} V[\bar{x} - \mu]$$

$$V[Z_o] = \frac{n}{\sigma^2} V[\bar{x}]$$

$$V[Z_o] = \frac{n}{\sigma^2} \cdot \frac{\sigma^2}{n}$$

$$V[Z_o] = 1.$$

Therefore,

$$Z_o = \frac{\bar{x} - \mu}{\sigma/\sqrt{n}}$$

is a valid standard normal test statistic for the population of values of $\bar{x}$. We may therefore determine values of $Z_{1/2\alpha}$ and $Z_{1-1/2\alpha}$ such that we will define an "acceptance region":

$$Z_{1/2\alpha} < Z_o < Z_{1-1/2\alpha} ,$$

for the hypothesis that $\bar{x} - \mu = 0$, with probability of error equals α. We may now compute from this acceptance region a "confidence interval" (bounded by confidence limits) within which the mean of the parent population may be asserted to lie, with $(1 - \alpha)$ percent confidence. This interval is determined by the following:

$$Z_{1/2\alpha} < Z_o < Z_{1-1/2\alpha}.$$

Letting

$$H = Z_{1-1/2\alpha},$$

$$-H = Z_{1/2\alpha} \text{ (since } Z_{1/2\alpha} = -Z_{1-1/2\alpha}),$$

and

$$Z_o = \frac{\bar{x} - \mu}{\sigma/\sqrt{n}} ,$$

we obtain

$$-H < \frac{\bar{x} - \mu}{\sigma/\sqrt{n}} < H$$

$$(-H)\ (\sqrt{n}/\sigma)\ < \bar{x} - \mu < (H)(\sqrt{n}/\sigma)$$

$$(-H)(\sqrt{n}/\sigma) - \bar{x} < -\mu < (H)(\sqrt{n}/\sigma) - \bar{x}$$

$$\bar{x} - (-H)(\sqrt{n}/\sigma) > \mu > \bar{x} - (H)(\sqrt{n}/\sigma)$$

$$\bar{x} + (H)(\sqrt{n}/\sigma) > \mu > \bar{x} - (H)(\sqrt{n}/\sigma)$$

$$\bar{x} - (H)(\sqrt{n}/\sigma) < \mu < \bar{x} + (H)(\sqrt{n}/\sigma)$$

$$\bar{x} - (Z_{1-1/2\alpha})(\sqrt{n}/\sigma) < \mu < \bar{x} + (Z_{1-1/2\alpha})(\sqrt{n}/\sigma).$$

Therefore, the lower confidence limit (LCL) of the mean of the parent population (μ) is given by

$$LCL = \bar{x} - (Z_{1-1/2\alpha})(\sqrt{n}/\sigma),$$

and the upper confidence limit (UCL) is

$$UCL = \bar{x} + (Z_{1-1/2\alpha})(\sqrt{n}/\sigma),$$

where $(1 - \alpha)$ is the desired "confidence level."

Under usual conditions, this procedure can be applied only when σ is known. If it is not known, its unbiased estimator ($\hat{S}$) can be substituted and the statistics $t_{1-1/2\alpha,d.f.}$ and $t_{1/2\alpha,d.f.}$ can replace $Z_{1-1/2\alpha}$ and $Z_{1/2\alpha}$, respectively, in the equations for UCL and LCL.

(The symbol d.f. denotes n-1 (degrees of freedom of the sample).) However, the t statistics need not be used in situations where a large sample (e.g., $n > 100$) is available (see ref. 10, pp. 520-521). In fact, examination of tables of the Z and t statistics indicates that the two distributions have approximately equal values of F(x) for $n > 100$ (for a given value of α) and that the t distribution converges on the Z distribution as d.f. approaches infinity.

Therefore, it remains only to show that $\hat{S}$ is an unbiased estimator of σ, where

$$\hat{S}^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2.$$

That is,

$$E(\hat{S}) = \sigma.$$

Note that $\hat{S}$ and σ are parameters of the parent population.

$$\sum_{i=1}^{n} (x_i - \bar{x})^2 = \sum_{i=1}^{n} [(x_i - \mu) - (\bar{x} - \mu)]^2$$

$$\sum_{i=1}^{n} (x_i - \bar{x})^2 = \sum_{i=1}^{n} [(x_i - \mu)^2 - 2(x_i - \mu)(\bar{x} - \mu) + (\bar{x} - \mu)^2]$$

$$\sum_{i=1}^{n} (x_i - \bar{x})^2 = \sum_{i=1}^{n} (x_i - \mu)^2 - 2(\bar{x} - \mu) \sum_{i=1}^{n} (x_i - \mu) + \sum_{i=1}^{n} (\bar{x} - \mu)^2$$

$$\sum_{i=1}^{n} (x_i - \bar{x})^2 = \sum_{i=1}^{n} (x_i - \mu)^2 - 2(\bar{x} - \mu)(n(\bar{x}-\mu)) + n(\bar{x}-\mu)^2$$

$$\sum_{i=1}^{n} (x_i - \bar{x})^2 = \sum_{i=1}^{n} (x_i - \mu)^2 - n(\bar{x} - \mu)^2.$$

Therefore,

$$E[\hat{S}^2] = \frac{1}{n-1} E\left[\sum_{i=1}^{n} (x_i - \mu)^2 - n(\bar{x} - \mu)^2\right]$$

$$E[\hat{S}^2] = \frac{1}{n-1}\left[E\left(\sum_{i=1}^{n} (x_i - \mu)^2\right) - n\ E(\bar{x} - \mu)^2\right]$$

$$E[\hat{S}^2] = \frac{1}{n-1}\ [n\sigma^2 - n\ \frac{\sigma^2}{n}]$$

$$E[\hat{S}^2] = \frac{1}{n-1}\ [(n-1)\sigma^2]$$

$$E[\hat{S}^2] = \sigma^2;\ \text{Q.E.D.}$$

The applicability of $\hat{S}^2$ as an unbiased estimator of σ^2 is thus shown. The standard equation for $\hat{S}^2$ offers the disadvantage that either the sample mean ($\bar{x}$) must be known before acquiring the values x_i or all values of x_i which are sampled must be stored. To alleviate this difficulty, the "calculation form" of the equation is derived as follows:

$$\hat{S}^2 = \frac{1}{n-1}\left[\sum_{i=1}^{n} (x_i - \bar{x})^2\right]$$

$$\hat{S}^2 = \frac{1}{n-1}\left[\sum_{i=1}^{n} (x_i^2 - 2x_i\bar{x} + \bar{x}^2)\right]$$

$$\hat{S}^2 = \frac{1}{n-1}\left[\sum_{i=1}^{n} x_i^2 - \sum_{i=1}^{n} 2x_i\bar{x} + \sum_{i=1}^{n}\bar{x}^2\right]$$

$$\hat{S}^2 = \frac{1}{n-1}\left[\sum_{i=1}^{n} x_i^2 - 2\bar{x}\sum_{i=1}^{n} x_i + n\bar{x}^2\right]$$

$$\hat{S}^2 = \frac{1}{n-1}\left[\sum_{i=1}^{n} x_i^2 - 2n\bar{x}^2 + n\bar{x}^2\right]$$

$$\hat{S}^2 = \frac{1}{n-1}\left[\sum_{i=1}^{n} x_i^2 - n\bar{x}^2\right]$$

$$\hat{S}^2 = \frac{1}{n-1}\left[\sum_{i=1}^{n} x_i^2 - n\left(\frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n^2}\right)\right]$$

$$\hat{S}^2 = \frac{1}{n-1}\left[\sum_{i-1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n}\right].$$

This is the most convenient form of the equation for the unbiased estimate of the variance of a parent population. This leads directly to the unbiased estimate of the population standard deviation ($\hat{S}$). This parameter may then be substituted into the equations for the UCL and LCL to obtain the limiting values of the confidence interval of interest.

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APPROVAL

EXPLANATION OF RANDOM EXPERIMENT SCHEDULING AND ITS APPLICATION TO SPACE STATION ANALYSIS

by John E. Moore

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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